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IDENTIFICATION OF PIPING AND SAPPING EROSION OF STREAMBANKS

by

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Final Report

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TO: All Report Recipients

1. The contract report transmitted herewith represents the results of the effort conducted under the work unit "River Bend System Hydraulics - Resisting Force Component" as part of the Flood Control Channels Research Program. The work unit is concerned with the problem of predicting the location and rate of bend erosion in flood control channels.

2. In order to understand bend erosion, it is necessary to investigate the mechanics of erosion due to various causes, including piping and sapping through soil stata, flow fields, rapid drawdown, vegetation, runoff, waves, and ice. The objective of the work unit is to reduce the legal and maintenance costs associated with the failure of unprotected river banks by developing criteria to determine bank erodibility.

3. The investigation reported herein addressed the erosion of river banks by exfiltrating seepage, referred to as sapping or piping. This mechanism is widespread in occurrence and is a significant factor in bank stability, but is often not recognized. The mechanism is complex and acts in concert with other processes of bank erosion and deposition. Operation of those other mechanisms often masks the processes and products of the piping/sapping mechanism. Failures caused by this mechanism may occur during periods of stream inactivity long after storm and/or flood events have ended.

4. The piping/sapping process is described in detail, and the conditions necessary for piping/sapping to occur are discussed. A procedure to determine whether or not piping/sapping is operating at an erosional bank site is presented. Also guidance on filter use to prevent or remediate streambank erosion caused by piping/sapping is given.

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13. ABSTRACT *(Maximum 200 words)*

The objective of this study was to investigate the erosion of river- and streambanks by exfiltrating seepage, referred to as piping and sapping. This mechanism is widespread in occurrence and is a significant factor in bank stability, but it is often overlooked. The mechanism is complex and acts in concert with other bank erosion processes. Operation of those other processes often masks the processes and products of piping/sapping. Failures caused by piping/sapping may occur during periods of stream inactivity long after storm or flood events have ended.

The piping/sapping process is described in detail, and the conditions necessary for piping/sapping to occur are discussed. A procedure to determine whether or not piping/sapping is operating at an erosional bank site is presented, along with guidance on filter use to prevent or remediate streambank erosion caused by piping/sapping.

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PREFACE

This report was prepared by Dr. D. J. Hagerty, University of Louisville, Louisville, KY, for the US Army Engineer Waterways Experiment Station (WES), Hydraulics Laboratory (HL), Vicksburg, MS. The study was sponsored by Headquarters, US Army Corps of Engineers (HQUSACE), under the Flood Control Channels Research Program (FCCRP). Mr. William A. Thomas, WES, HL, was FCCRP Program Manager. Technical Monitor, HQUSACE, was Mr. Thomas E. Munsey. The study was done under Work Unit No. 32550, "River Bend System Hydraulics-Resisting Force Component" and was conducted during the period from September 1989 to September 1990.

This report discusses the erosion of streambanks by the piping and sapping process. Parts I, II, and III discuss the identification of erosion by piping and sapping. Part IV provides guidance on the prevention or remediation of streambank erosion caused by piping and sapping.

Messrs. Bradley M. Comes, Mathematical Modeling Branch (MMB), and Michael J. Trawle, Chief, MMB, monitored the study under the supervision of Mr. Marden B. Boyd, Chief, Waterways Division, and Mr. Frank A. Herrmann, Director, HL, WES.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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CONTENTS

IDENTIFICATION OF EROSION BY PIPING AND SAPPING

PART I: INTRODUCTION

1. This description of the process of piping and sapping erosion is intended for persons with little experience in the investigation of streambank erosion in the field. A simple explanation of the causes and mechanics of the process is presented first. To illustrate those mechanics, a typical sequence of events in which a bank is subject to piping/sapping is described. Conditions which are necessary to the piping/sapping process are described; even though a particular condition may be necessary to the process, satisfaction of that condition alone may not be sufficient to cause bank erosion to occur by the piping process. The major portion of this text is a description of evidence, direct and indirect, which indicates that piping and/or sapping has occurred on a given bank site. Direct evidence is limited to the condition of water actually flowing out of a bank and removing soil particles, in the sight of an observer or under detection by a monitoring device such as a motion picture camera. Indirect evidence includes primary evidence such as cavities in the bank face and deposits of removed particles in deltas or fans below a piping/sapping zone. Secondary indirect evidence is provided by features which suggest the emergence of water from a particular part of a bank face and/or the removal of soil particles by the seeping water. Third-order indirect evidence includes features and conditions which can be caused by the piping/sapping process but which also can be caused by other erosion processes; such evidence obviously must be supplemented with more definite proof before an identification of erosion process(es) can be made. Finally, possible interactions among piping/sapping and other streambank processes are described; such interactions may make identification of piping/sapping very difficult.

The Piping/Sapping Process

2. If water flows out of a streambank under a sufficiently high hydraulic gradient, the exfiltrating water can remove particles of soil from the bank face. This movement of soil particles by seeping water in soil voids is called internal erosion. Should the flow be concentrated by variations in

hydraulic conductivity or by restriction of water supply (as from a leak from an underground pipe), the exfiltrating water can create cavities in the bank face. Because such cavities commonly have roughly cylindrical shape and are oriented virtually perpendicularly to the bank face, they have been called "pipes" and the internal erosion process by which they form has been called "piping." The occurrence of internal erosion in earth dams and the appearance of "pipes" on downstream dam faces and abutments have been recognized for many years. If exfiltration occurs over a broad area so that multiple "pipes" form or larger lenticular cavities appear, this process may be called "sapping." This term derives from an older usage—"spring sapping"—which was used to describe the excavating action (sapping) of water flowing vigorously out of the soil (a spring).

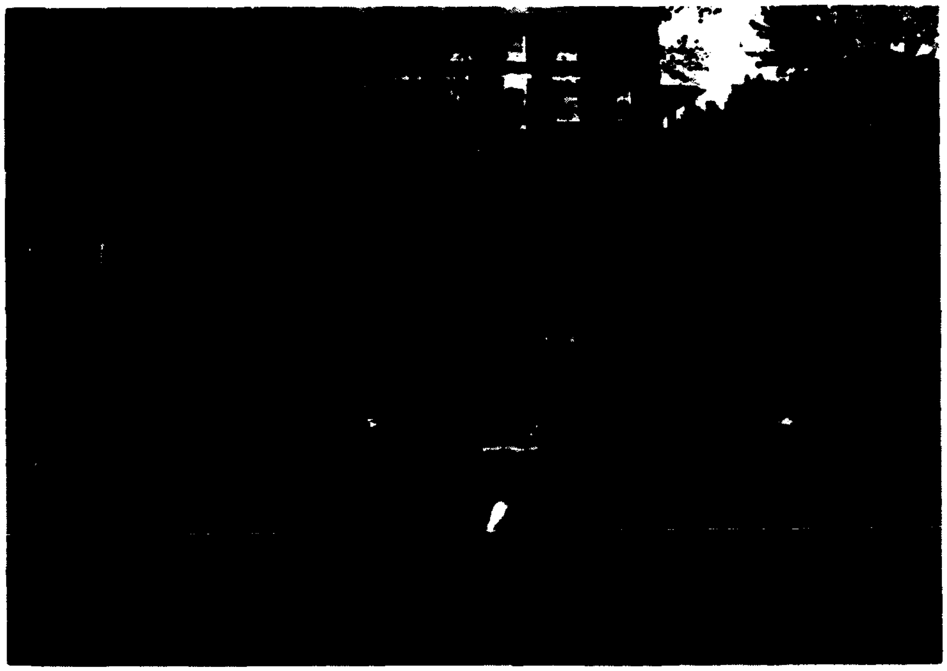
3. This process can be significant because the mechanism tends to intensify; removal of soil at the exfiltration face shortens the seepage path and increases the hydraulic gradient which causes the outflow. If the source of water is constant or is replenished periodically, the internal erosion tends to intensify. In an earth dam, this intensification can cause the seepage cavity or "pipe" to reach the stored water body, with catastrophic results. Even if the pipe or sapping cavity does not approach a body of stored water, local instability may be created in the soils above the cavity. Failure and erosion of streambanks occur by instability of bank soils undercut by piping cavities. Figure 1 shows streambanks which exhibit features typical of the piping/sapping process.

4. To illustrate the mechanism of soil removal from a streambank by internal erosion, the formation of cavities, and the subsequent collapse of undermined upper-bank zones, a hypothetical bank can be subjected to conditions which lead to piping and sapping. This imaginary streambank is shown in Figure 2. The bank is alluvial in origin and consists of a series of nearly horizontal layers. Soil texture and permeability vary from layer to layer. At the beginning of the sequence, the adjacent stream is at a low level and the owner of the riparian land has graded the bank to improve access and appearance (Figure 2a). Soon afterward, the stream rises and inundates the bank, causing water to be recharged into the bank, particularly into the more pervious layers (marked "p" in Figure 2b). When the stream drops back to low levels after the flood, stored water flows out of the bank, exfiltration is concentrated at the pervious layers, and cavities form as soil particles are

a. Multiple piping/sapping layers in bank

b. Collapse of soil undermined by sapping

Figure 1. Streambanks exhibiting features typical of piping/sapping process (Sheet 1 of 3)



c. Piping/sapping features

d. Piping/sapping with collapse of undercut layer

Figure 1. (Sheet 2 of 3)

e. Multiple piping/sapping horizons in high bank

f. Multiple sapping horizons, Li River, China

Figure 1. (Sheet 3 of 3)

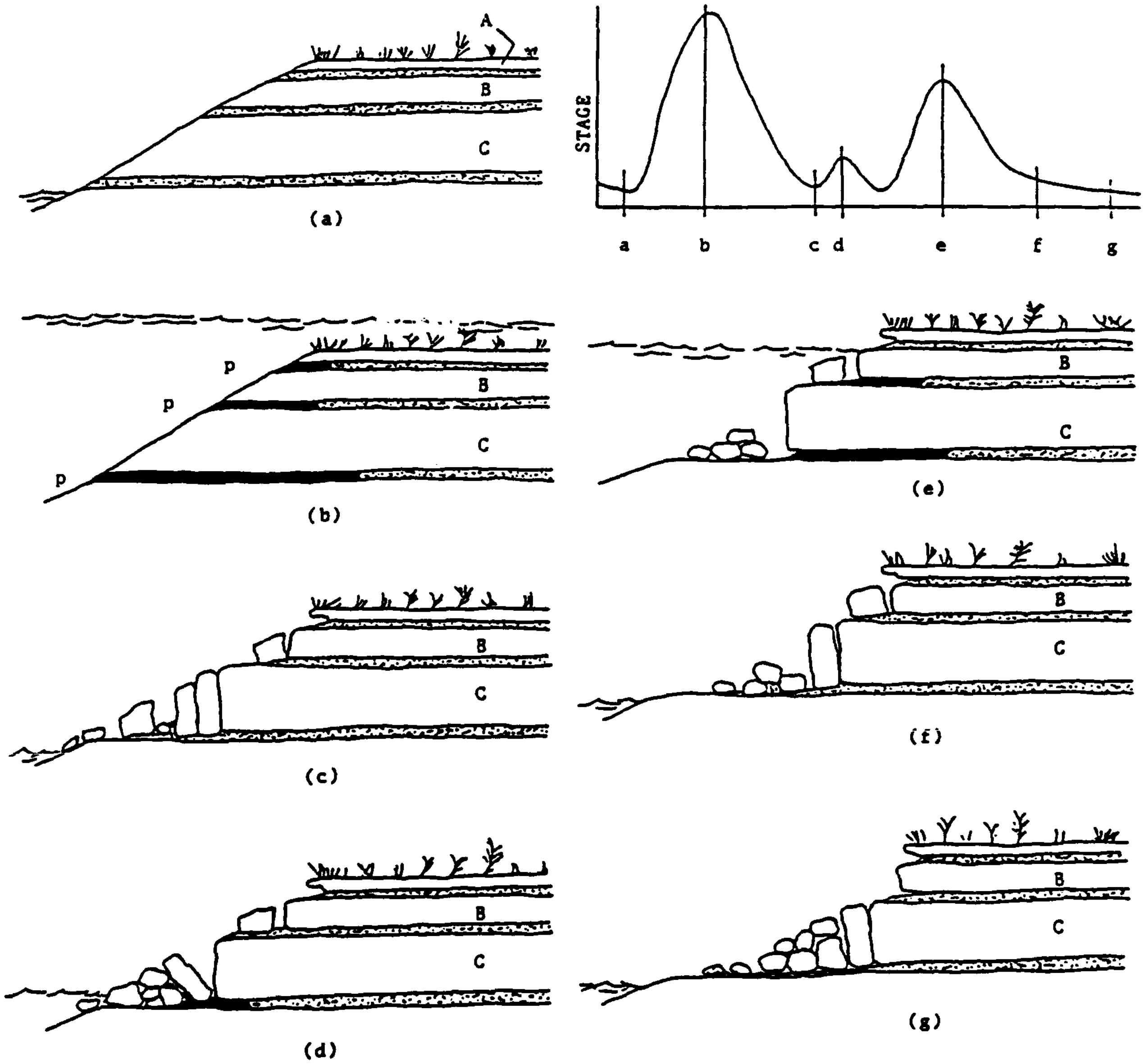


Figure 2. Sequence of stage fluctuation with attendant recharge into pervious zones (sections b, d, and e) and subsequent piping/sapping and failure (sections c, f, and g)

removed (Figures 2c and 2d). Under upper-bank zones fail long after the flood recession (Figure 2c). During a subsequent flood, failed soil blocks are eroded and/or removed and lower pervious zones are recharged. After recession of the second flood, outflow reworks failed soil blocks, deposits fans and extends cavities, with minor delayed failures of undercut zones (Figure 2g).

5. The sequence of events on an actual streambank will depend upon many factors including hydrograph parameters (primarily maximum stage and duration of flood rather than shape of hydrograph), permeability and density of pervious layers, strength and thickness of undercut layers, and bank geometry (inclination of layers, overall slope, etc.). The source of water for the process may be natural groundwater seepage, or leakage from a conduit or tank, rather than bank recharge. Other processes such as tractive force scour may act with the piping/sapping to remove bank soils or may deposit sediments on the bank and counteract the piping/sapping action.

6. What conditions must prevail for internal erosion to occur in a streambank? What circumstances are necessary for piping or sapping to remove particles of bank soil? What factors tend to accelerate piping/sapping and which tend to counteract the effects of this erosion process? The remainder of Part I contains answers to these questions.

Conditions Necessary to Piping

7. Among the circumstances that must prevail if piping or sapping is to happen, the one condition which is absolutely necessary is concentrated flow of intensity sufficient to remove an in situ particle of soil, entrain it, and carry it away from its point of origin. A source of water must be available to supply the requisite flow; the source need not be constant since the process can be active intermittently. Concentration of flow is necessary to achieve the flow intensity sufficient to remove soil particles. Flow may be concentrated by differences in hydraulic conductivity between various zones or layers in the bank or by restriction of the inflow of water to a discrete location or source. Finally, for internal erosion to produce cavities, there must be a free face or an external plane from which the water can move the soil particles; i.e., piping cannot occur if an external layer or filter allows the exfiltrating water to pass but retains the destabilized

particles or if both water and particles are retained by an overlying or masking berm.

8. Exposed face. There must be an exit point by which seeping water can leave the bank and carry along dislodged particles, or piping cavities will not form. While this statement may seem to be simplistic, it has considerable significance. If collapses of overlying soil zones, for instance, cause the face of a pervious layer in a streambank to be covered and masked, the exfiltration of water will be impeded. The flow will be retarded and the internal erosion will be delayed until exfiltration has been reestablished and that exfiltration has removed the material covering the piping zone. Deposition of sediments over exfiltration zones during high-water periods can have similar effects. On the other hand, removal of failed soil blocks, lumps and loose particles by tractive force scour can reexpose an exfiltration zone and accelerate piping and sapping. Other mechanisms also may remove failed soil or sediments masking piping faces. In any event, an exposed face is necessary for the continued removal of soil particles by exfiltrating water.

9. Concentrated flow. Creation of nearly cylindrical "pipes" or lenticular sapping cavities in a streambank face requires concentration of flow at the locations where the cavities can form. Concentration of flow may occur because the source of water is of very limited areal extent; for example, concentration of flow may occur because the source of water is a leaking joint in a wastewater pipe buried behind the bank face. Overland flow may be collected in ditches, and water may enter the bank system through soil cracks which intersect a ditch; i.e., only a limited portion of the bank becomes sufficiently wet to cause exfiltration.

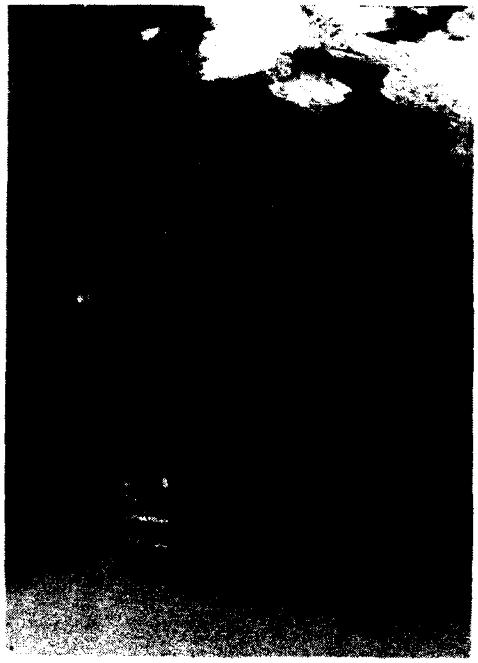
10. By far, the most common cause of concentration of flow in natural streambanks, however, is variation in hydraulic conductivity among bank soil layers or zones. This effect is most significant in alluvial streambanks where the banks consist of layers of soil with varying texture, porosity, and hydraulic conductivity. The hydraulic conductivity of a layer of clean sand may be several orders of magnitude larger than the conductivity of a sandy silt layer. In contrast, a silty clay layer may be virtually impermeable compared to a silty sand stratum.

11. If flow of seeping water is concentrated in a particular layer or at a particular location, piping or sapping can occur there if the hydraulic gradient causing the exfiltration is sufficiently high. Should particle

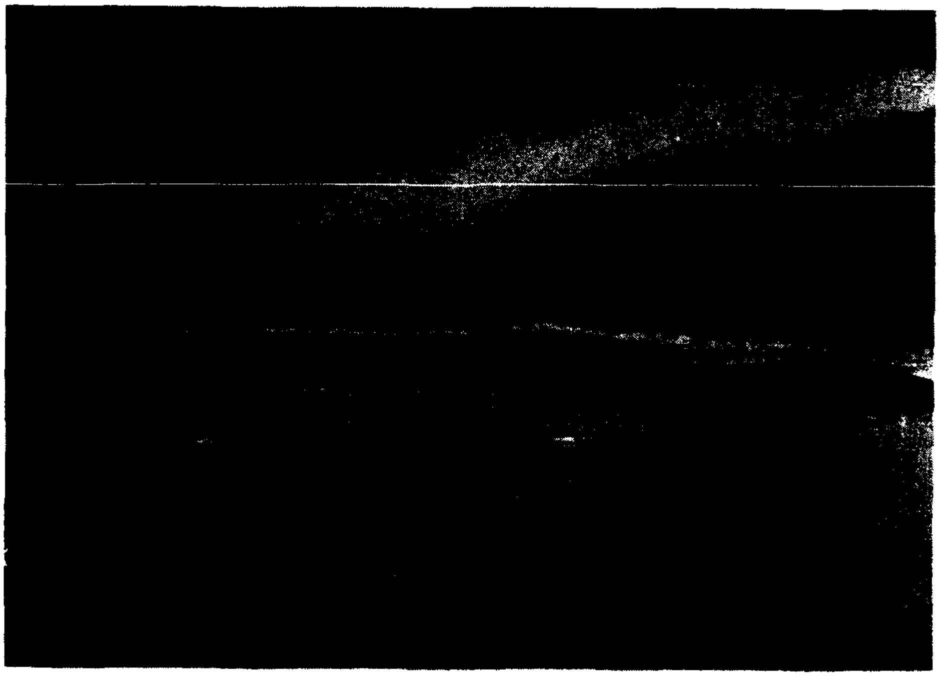
removal be concentrated in a particular zone, removal of particles will tend to shorten the seepage path and increase the hydraulic gradient at the zone of removal. Local increase in gradient serves to capture more seepage and further to concentrate flow. Once started, formation of cavities will tend to accelerate if the supply of water to the exfiltration zone remains undiminished.

12. Sources of water. The most obvious source of water to supply the piping/sapping process on a streambank is the stream itself. When the stream rises against the face of the bank, water enters the bank soils. Recharge will be greatest into those soil zones which are most pervious and in which no preexisting hydraulic gradient exists to cause a countervailing outflow. Of course, if the head in the stream exceeds that in the bank, outflow will cease and recharge will occur. The volume of water stored in any one soil zone or layer will depend upon the hydraulic conductivity of that layer, the difference in head between the stream and the water in the layer, the area of the layer exposed in the bank face, and the time during which recharge occurs, as well as other less important factors. If some prior instability in the bank soil mass has created tension cracks through layers of low permeability, more pervious layers will be connected hydraulically through those cracks, at least to some degree. Water entering a pervious layer exposed in the face of the upper bank may find its way to lower layers not exposed (perhaps masked by failed soils or sediments) by means of cracks. Water stored in floodplain depressions during periods of inundation of the entire bank may flow down gradually to lower bank layers through cracks, and piping may continue for long after the flood event as the depression storage is released at the exfiltration zones in the bank face. Figure 3 shows sites where depression storage supplies active sapping zones.

13. Surface precipitation and overland flow also can supply water to a piping zone in a bank face if the surface water flows into cracks which penetrate down from the terrace or floodplain surface into the pervious zones or layers in the bank. Surface water filling cracks in the bank creates hydrostatic pressure which tends to lift and push toward the stream any blocks or slabs undercut by piping action in a lower layer. Irrigation water, supplied by ditches or sprays, can seep down through cracks to cause continuation of piping or sapping at the streambank faces of pervious underlying soil layers. Because surface water may be supplied at times when the stream is inactive

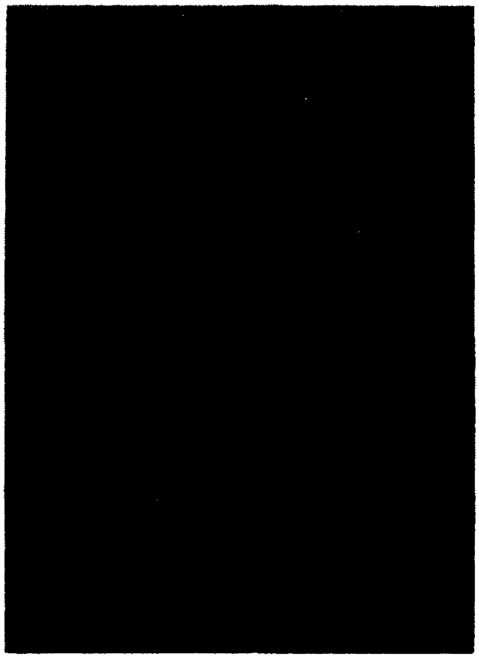


a. Temporary storage behind piping zone in bank



b. Water-filled depression behind failing bank

Figure 3. Sapping zones supplied by depression storage (Continued)



c. Depression storage (bottom) behind gully being formed by piping erosion

d. Head of gully shown in Figure 3c

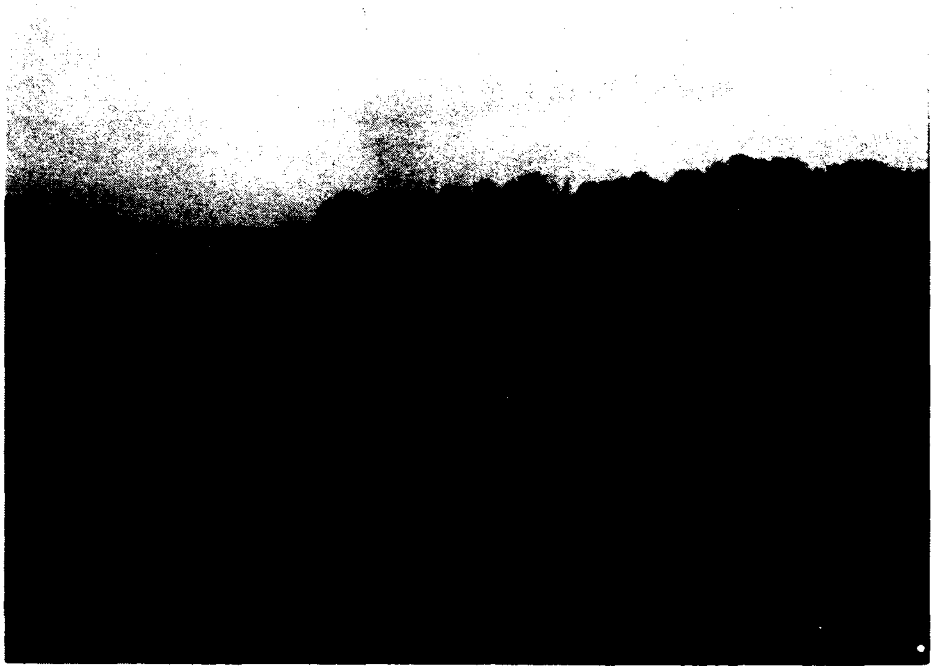
Figure 3. (Concluded)

(little rise or fall in stage), piping may occur and may cause local failures in undercut layers, with no apparent relation to stream activity.

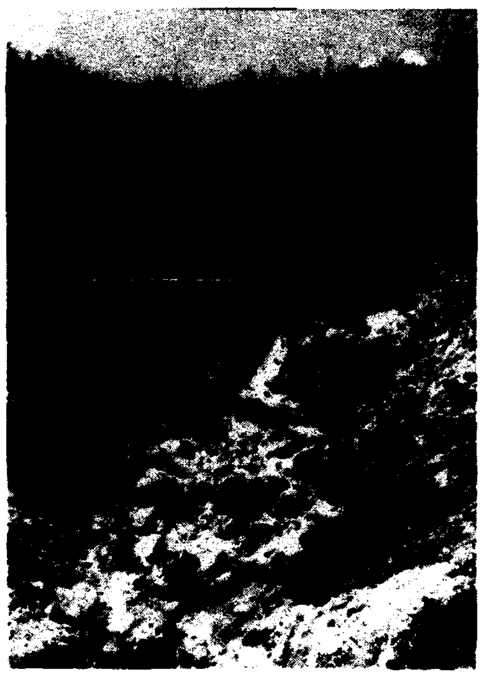
14. A third category of water sources for internal erosion is subsurface leakage from conduits or containment vessels. A very common circumstance is collapse and instability in streambanks at points where agricultural drains empty. In many cases, the joints between sections of drain pipe leak collected water back out into surrounding soil. When this happens near the outfall of the drain in a streambank, the leaking water adds weight to the soil, and decreases the strength of the soil. If water seeps down into pervious layers subject to sapping at the bank face, the sapping can undercut the weakened soil around the drain causing failure in the soil. Continued leakage and consequent sapping can lead to deflection and displacement of the drain, with greater leakage at the deflected (more open) joint. Failure around the drain can become a progressive process. Figure 4 shows an example of piping failure around a drain outlet.

15. Another example of leakage from a "containment" facility is outflow from a septic tank treatment system. For many dwellings along streams in rural areas, no sewer service is practicable. Collected wastewaters are discharged to a buried tank fitted with radiating lateral exfiltration conduits. The water introduced into the subsoils in this way can activate piping and sapping at faces of the more pervious subsoils exposed in an adjacent bank. Leaking water supply pipes, sewers, or underground storage tanks also can supply water to activate piping and sapping in adjacent streambanks.

16. Adequate exit gradient. Piping or sapping cannot occur unless some source of water supplies a concentrated flow to an exfiltration zone in an exposed face. Nevertheless, piping or sapping will not occur unless the hydraulic gradient at the exfiltration face is sufficient to remove soil particles and transport them away from the exfiltration zone. What value of hydraulic gradient will be required? The resistance of soil particles to removal by seeping water will depend upon the degree of interference from adjacent particles with respect to the incipient motion. This interference in turn depends upon the density of particle packing as well as particle shape and variation in particle size. All other factors being equal, a dense arrangement of angular particles of various sizes will be more resistant to movement by seeping water than will a loose arrangement of rounded particles of uniform size. Resistance to movement also will depend on the average



a. Cusp in bank caused by piping erosion at drain



b. Head of cusp; broken drain tile in soil debris (foreground), tile in place in bank

Figure 4. Examples of piping failure around drain outlet (Continued)

c. Close view of drain tile shown in Figure 4b, slab fallen from below drain

Figure 4. (Concluded)

forces between particles and the degree of confinement of the pervious layer or zone furnished by adjacent less pervious soils. All of the parameters mentioned thus far can vary and do vary from point to point in a natural streambank. For this reason, it is virtually impossible to predict at a given location on a specific site what value of gradient will be sufficient to cause particle removal. If bank soils vary significantly in hydraulic conductivity, it is very difficult even to measure, by means of piezometers, the actual water pressures in bank soils. Thus, it is practical only to evaluate the relative difficulty of particle removal from various layers on the basis of the parameters described previously; the gradient required to activate piping is inversely related to the difficulty of particle removal.

17. Summary. Since piping and sapping will not occur unless the hydraulic gradient at an exfiltration face is sufficient to cause particle removal, but it is virtually impossible to predict the gradient required to cause such removal, why is it important to evaluate sources of water, conditions which promote concentrated flow, and degree of bank face exposure? Evaluation of these parameters is necessary to the evaluation of piping/sapping potential. If abundant water is available to cause concentrated flow to exposed exfiltration zones in a streambank, it is highly probable that piping or sapping will occur in that streambank in the future. Is piping occurring there now, or has it occurred there in the past? To answer this question, it is necessary to observe the process occurring on the site or to assemble evidence which indicates that the process has been active on the site. Part II contains a description of such evidence.

PART II: EVIDENCE OF PIPING/SAPPING

18. To determine that piping or sapping has caused instability and erosion at a particular site, it is necessary to obtain positive evidence that the process is operating or has operated at that location. Direct evidence is likely to be obtained only seldom; indirect evidence usually is much more readily available. Some indirect evidence strongly indicates that piping/sapping has occurred while other indirect evidence is only suggestive.

Direct Evidence

19. It is possible to observe piping and sapping and thus obtain first-hand proof that the erosion process is operating on a particular site. Figure 5 shows situations in which investigators actually observed water flowing out of cavities in streambanks and carrying soil particles out of the bank. At times, such flow occurs below stream level; for example, after water has been recharged into a bank during a flood, pervious layers will begin to discharge water back into the stream when the gradient within any layer is directed toward the stream. Soil particles can be moved out of cavities into the streamflow while those cavities are still covered by receding waters. In such cases, it is sometimes possible to detect the outflow from the sapping bank seams, by a perceived difference in temperature in the water, i.e., the exfiltrating groundwater is warmer or cooler than the stream water. If the outflow is vigorous, it may be possible to catch (in cupped hands near the bank face) the dislodged soil particles as they leave the bank face. All too often, however, when an investigator visits a site, stored recharge or intermittent groundwater exfiltration is not occurring and piping/sapping can be detected only through indirect evidence.

Indirect Evidence

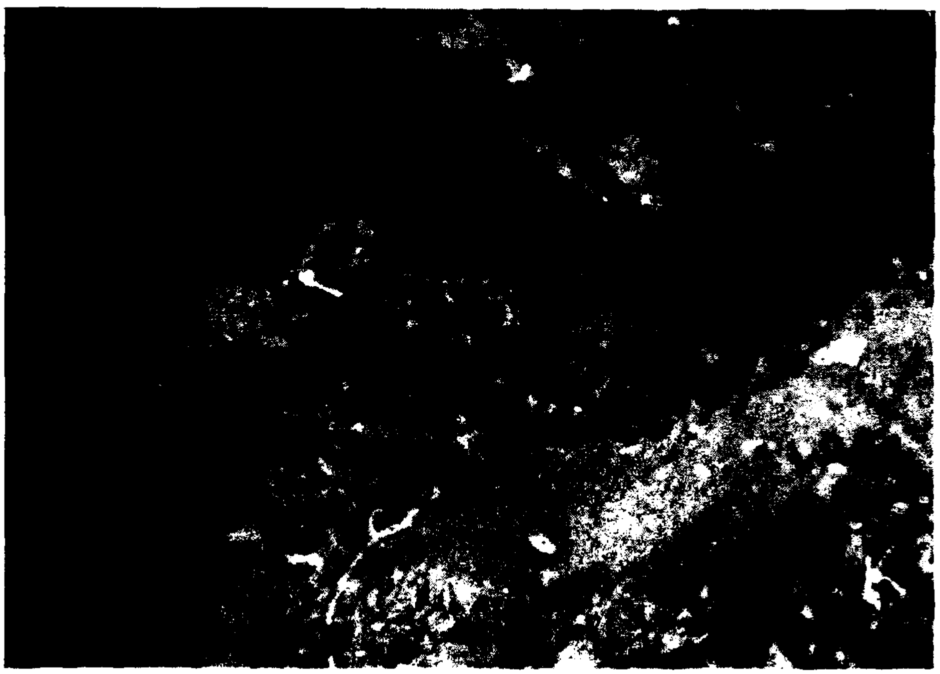
20. Three sorts of indirect evidence of piping/sapping can be described: primary indirect evidence consisting of features that are caused solely or predominantly by the piping/sapping process; secondary indirect evidence consisting of features which strongly suggest that the piping/sapping process has been operating on a site; and tertiary evidence consisting of features or

a. Water and soil flow out of bank

b. Water and soil flow (coin is U.S. dime)

Figure 5. Direct evidence of piping/sapping erosion process (Sheet 1 of 3)

c. Exit point, water carrying
sand grains out of bank



d. Water and sand flow (just below area in
Figure 5c)

Figure 5. (Sheet 2 of 3)

e. Silt and water (top) flow out over sand

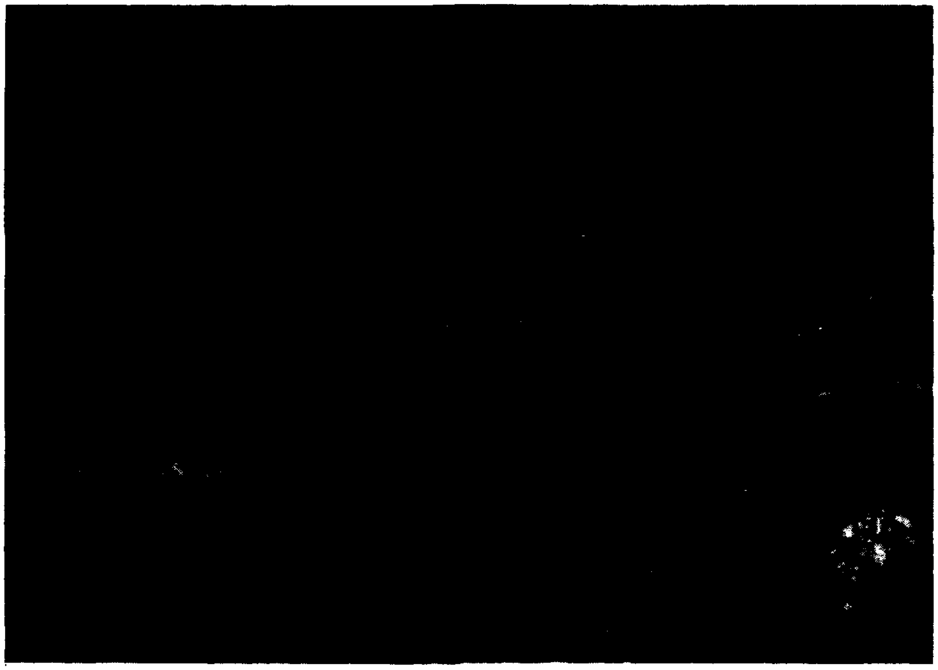
f. Fine sand and water flow out of sand

Figure 5. (Sheet 3 of 3)

conditions which suggest the possibility that piping/sapping may have occurred. Tertiary evidence includes features which can be caused by piping/sapping but may also be caused by other mechanisms. Tertiary evidence also may be short-lived features which tend to disappear with time. Finally, tertiary evidence includes features or circumstances which tend to suggest that other mechanisms have not operated on a given site.

21. Primary indirect evidence. Among the features which are caused solely or predominantly by piping/sapping are the cavities excavated in a bank face by exfiltrating water. Figure 6 shows a variety of the cavities that have been observed at sites where exfiltrating water has been concentrated by some circumstance. If the existence of a soil layer with hydraulic conductivity higher than surrounding layers has concentrated flow in that relatively more pervious zone, then a relatively narrow but long array of almost circular holes may be produced, particularly if the shear strength of the pervious layer is sufficiently high to allow the formation of many cavities without a collapse. If the pervious zone is thick and outflow is perched on a lower less pervious zone, the upper part of the pervious layer may dry and lose apparent cohesion. In such a case, loose soil grains from the upper part of the pervious zone fall in front of and mask the piping cavities. If the concentration of outflow is caused by the local nature of the water source (a point source such as a wastewater disposal tank and lateral field), the piping/sapping cavities may occur in several layers in a given zone of the bank face rather than in a wide relatively short zone at the face of a given pervious layer. If overlying less pervious zones show high shear strength, individual roughly cylindrical holes may coalesce to form wider lense-shaped cavities. The aspect (height-to-width) ratio and size of the piping/sapping cavities depend upon the shear strength of the sapping layer and the overlying less pervious layer (if any). Piping cavities as large as 2.5 ft (0.8 meters) in diameter have been observed in thick silty sand layers overlain by strong clayey silt layers. Depths of sapping cavities vary commonly between several inches and 10 to 15 ft (3 to 5 meters), but piping cavities many feet long have been reported by a number of investigators. Very long piping cavities usually suggest relatively shallow pervious soil zones (the piping/sapping zone) overlain by soils strengthened by root systems.

22. Because of the activity of various bird species, notably riparia riparia, in forming nests in cavities in sandy streambanks, holes formed by

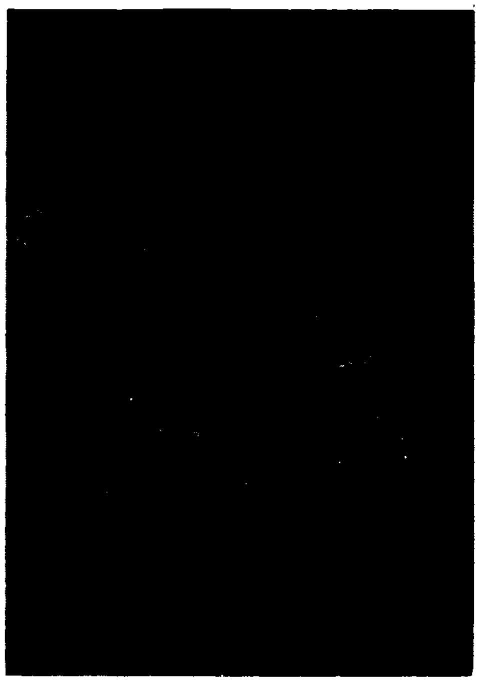


a. Piping/sapping cavities, Ohio River bank

b. Multiple zones of sapping cavities, Red River bank

Figure 6. Variety of cavities formed by exfiltrating water (Sheet 1 of 7)

c. Field book in piping cavity, Kanawha River bank



d. Piping cavities above sapping zone, Red River bank

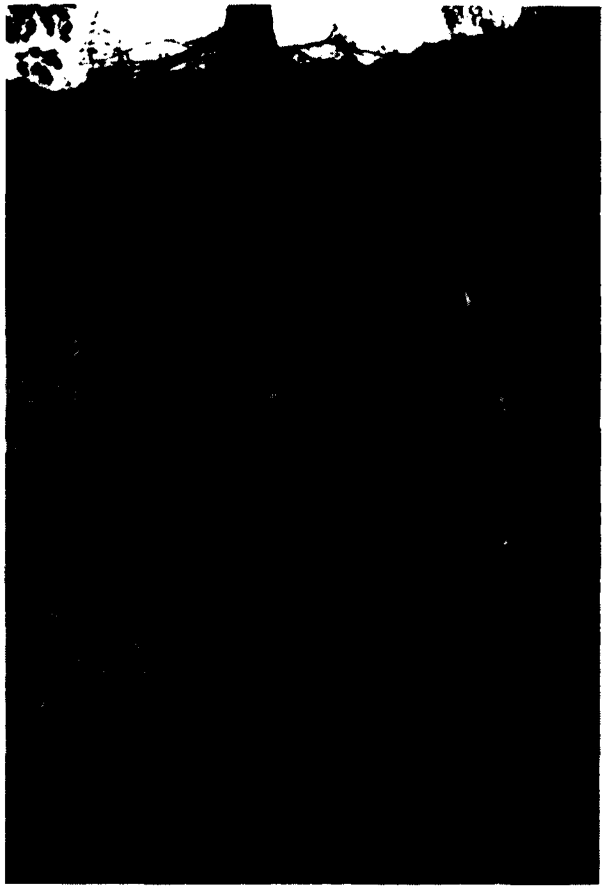
Figure 6. (Sheet 2 of 7)

e. Field book in piping cavity

f. Piping cavities in recent sediments over stiff cohesive soil layer

Figure 6. (Sheet 3 of 7)

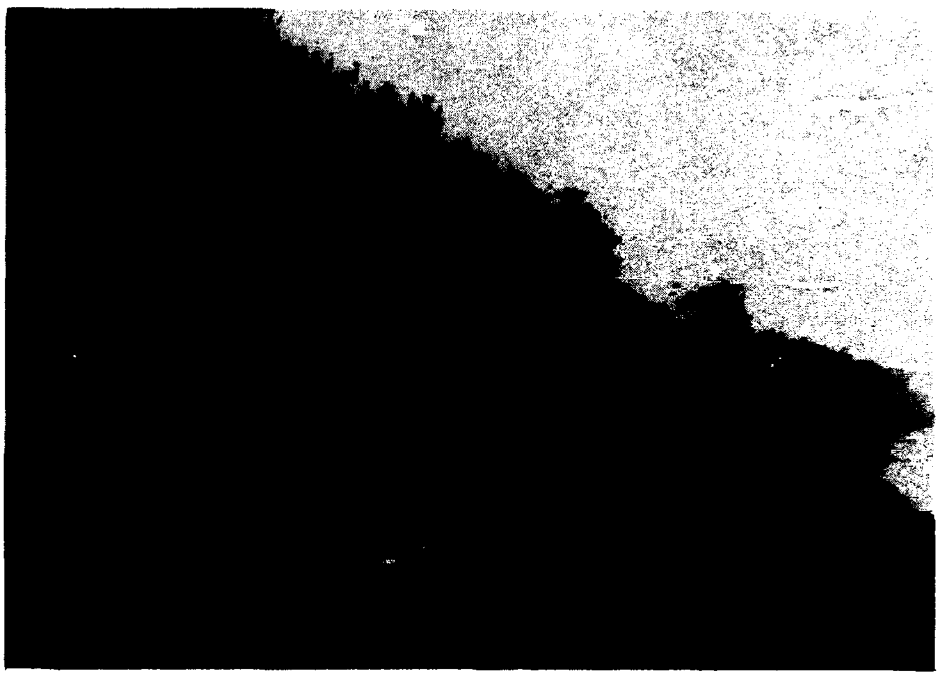
g. Piping cavity in upper bank, slabs above cavity



h. Sapping zone in lower bank

Figure 6. (Sheet 4 of 7)

i. Piping cavities in bank shown in Figure 1e (Note sapping scarps in foreground)



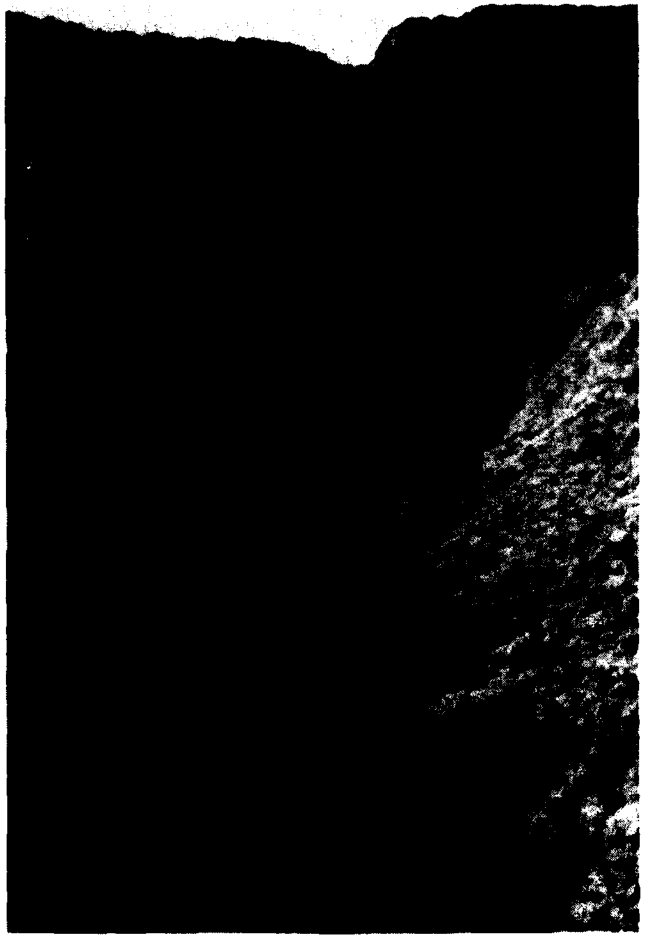
j. Different view of piping cavities in bank shown in Figure 1e

Figure 6. (Sheet 5 of 7)

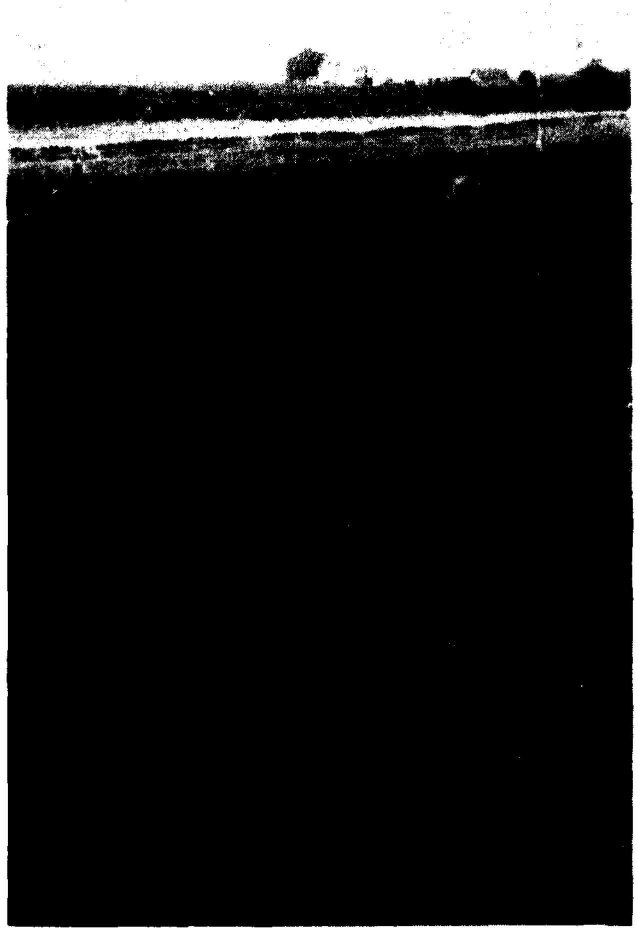
k. Close view of cavities shown in Figure 6j (Note evidence of sand flow, right side of figure)

l. Close view of cavities shown in Figure 6k (coin is U.S. dime)

Figure 6. (Sheet 6 of 7)



m. Piping cavity and tensile failure. Subsurface drainage from field was source of water



n. Same cavity shown in Figure 6m. Note absence of surface runoff features

Figure 6. (Sheet 7 of 7)

the piping mechanism have been attributed mistakenly to these bank-dwelling birds. Cavities formed by piping subsequently may be occupied by nesting birds, because at the time the holes were being formed, typically in wet spring weather, the birds were not present. During dry weather when outflow ceases, opportunistic birds may occupy or even enlarge the cavities formed by the internal erosion. Figure 7 shows cavities enlarged by bank swallows. Exercise of judgement usually will indicate easily the real origin of the cavities found in a bank face. Particularly useful in making such judgements is a second type of primary indirect evidence of piping/sapping: the presence of small fans or deltas of soil particles in front of and/or below the aforementioned cavities.

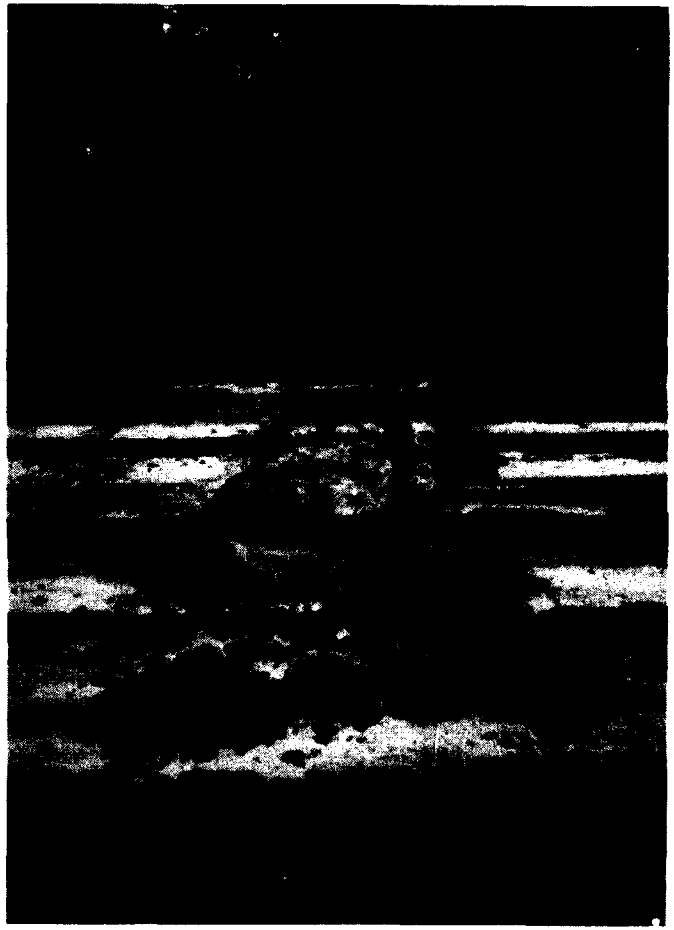
23. If exfiltration has continued on a bank site during a period when the stream has been inactive and no process has operated to remove the debris from piping and sapping activities, accumulations of soil particles can form in front of and below the cavities from which the particles came. Often when exfiltrating water emerges from a cavity bearing entrained soil particles, the flow spreads and deposits the eroded particles. Small fans or deltas may form if the flow spreads on top of a resistant less pervious layer exposed in the bank face below the piping/sapping zone. Figure 8 shows some of the small accretion zones that have been observed below piping cavities. These deposits typically form at an angle of 30 deg or less, to the horizontal, if the transported soil particles are sand-size or larger. When silt or clay particles are piped out of a particular layer, they may be deposited as thin films or skins on the faces of lower zones in the bank if those lower zones are more pervious. Figure 9 shows a film of silt and sand particles which had been piped out of a layer high in a bank face by outflow perched on a clay layer. As the silt-bearing water flowed down over the face of the bank, the flow passed over a lightly cemented sand layer into which the water drained, leaving the film of particles shown in the figure.

24. The deposits of piped-out particles found in front of and below exfiltration cavities tend to be very loose and easily eroded by tractive forces, by wind, and by surface runoff passing down and over a bank face. Consequently, these features are somewhat ephemeral. Nevertheless, they are strong indicators that a piping/sapping process has been operating.

25. Secondary indirect evidence. Indirect evidence which indicates that piping and sapping have occurred at a site or that the potential for

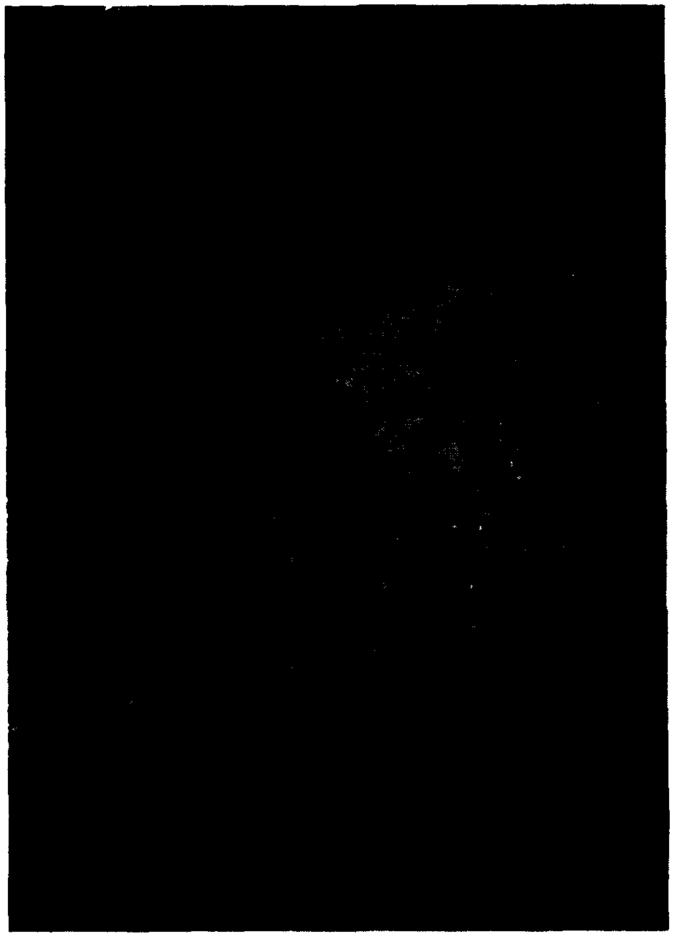
Figure 7. Piping cavities enlarged by bank swallows with marks of birds' activities still visible

a. Fine sand "fan" below piping cavity (top) in bank

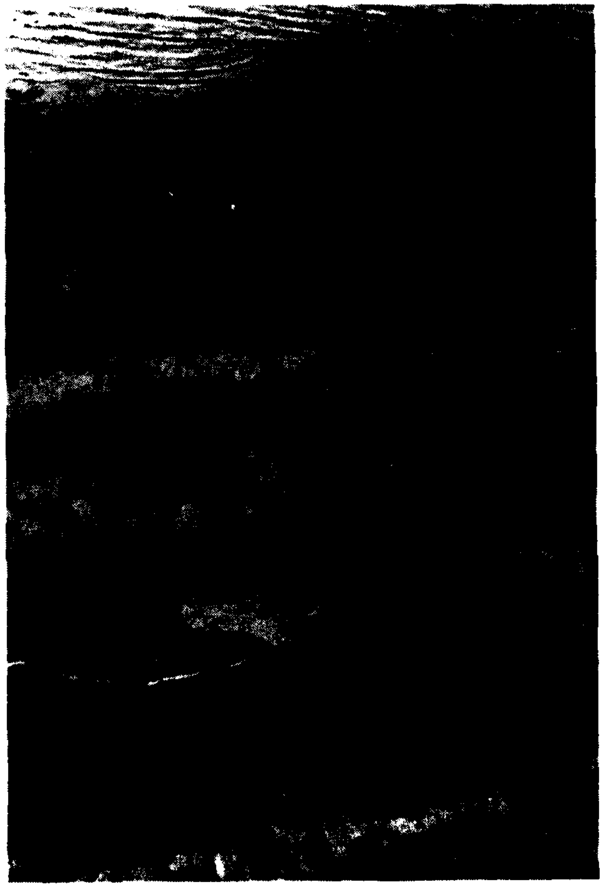


b. Piping zone (top), multiple scarps and "fans" of piped-out particles on soil

Figure 8. Accretion zones below piping cavities (Continued)



c. Piping zone (top) and sand piped piped out and over riprap



d. View down bank; piped-out soil over drift wood (at bottom) and runnels cut in "fans" by continued outflow of water

Figure 8. (Concluded)

a. Fine sand and silt, carried by flow out of upper-bank piping zone and deposited in front of lower sapping cavities

b. Fine sand and silt flow film over and in front of piping cavities

Figure 9. Examples of fine sand and silt deposited on faces of lower, more pervious zones

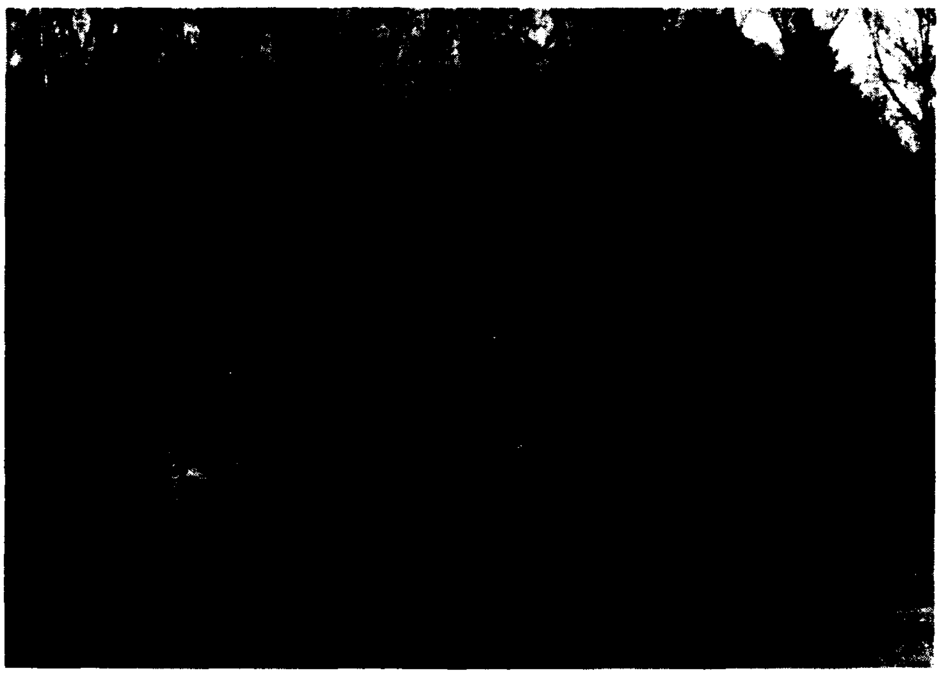
piping/sapping is significant, but which lacks the strong diagnostic character of cavities in the bank face and/or soil deposits below and in front of cavities, can be termed secondary indicators. Secondary indirect evidence includes features such as gullies or rills which indicate that water has flowed out of the streambank. In order for these features to be indicators of piping activity, they must show that the water which formed the gully or rill exfiltrated from the bank face and did not flow down and over the bank from higher elevations. The gullies must be "blind"; that is, they must originate at the exfiltration zone. Such features are not at all uncommon. Piping long has been recognized as a major contributor to the formation of gullies in arid lands. Since the mid-1960's, piping and sapping have gained increasing recognition as important mechanisms in the drainage of watersheds in humid climatic zones and in the formation of gullies in upland watersheds.

26. Figure 10 shows some instances of gullies and rills originating at exfiltration zones in streambanks. In some cases, exfiltration out of pervious bank zones may be sufficient to initiate rills or gullies below the exfiltration zone(s), but the flow may not be sufficiently concentrated to create cavities at the exfiltration face itself. In other cases, the flow may be concentrated near the bottom of a thick but weak pervious layer in which cavities form but are covered or masked quickly by collapse of upper parts of the weak layer; in such cases, no cavities may be visible, but the outflow may be sufficient to erode gullies or rills below the outflow zone.

27. Gullies and rills are most likely to form below piping cavities if the bank face consists of multiple levels or layers, and the layers below the exfiltration cavities are erodible or are covered with erodible materials such as deposits of loose or soft recent sediments. Because circumstances favorable to the formation of gullies below piping cavities inherently correspond to the presence of erodible soils, these gullies and rills are vulnerable to erosion mechanisms other than downcutting by outflow from piping holes. Stream currents during a period of high water, waves generated by wind or vessels, or winds may obliterate the gullies and rills caused by piping outflow. Thus, these features tend to be short-lived and transitory.

28. Another feature which indicates that conditions favor the occurrence of piping and sapping is the presence of staining on the face of the bank, particularly if the staining occurs in patterns which suggest exfiltration. Seeping groundwaters can dissolve minerals from the soils and rocks through

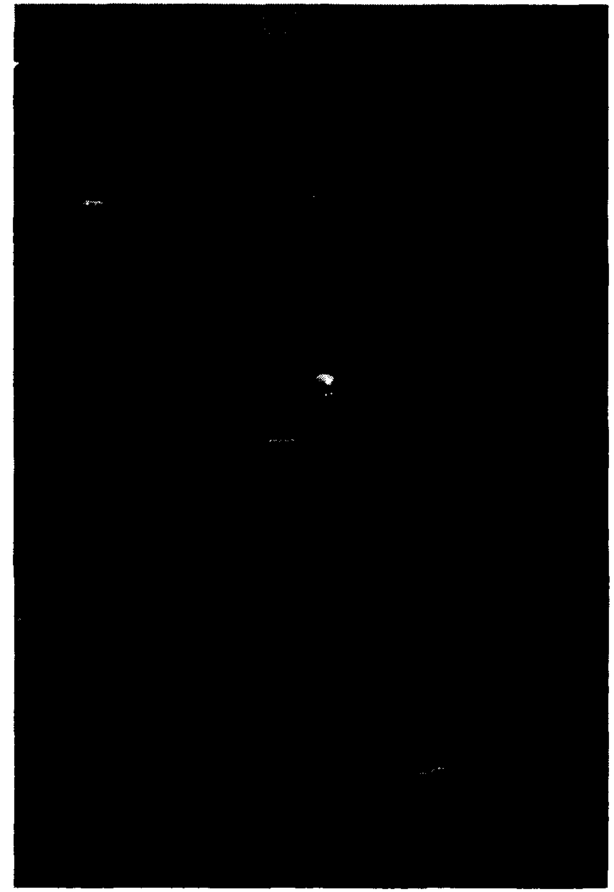
a. Blind gully at piping zone in Ohio River bank



b. Blind gullies and multiple scarps below piping zone in upper bank, Red River, Louisiana

Figure 10. Instances of gullies and rills originating at exfiltrating zones in streambanks (Sheet 1 of 3)

c. Soil and water flow in blind gully in bank of Illinois River



d. Blind gullies and multiple scarps below piping zone in bank of Eighteenmile Island, Ohio River

Figure 10. (Sheet 2 of 3)

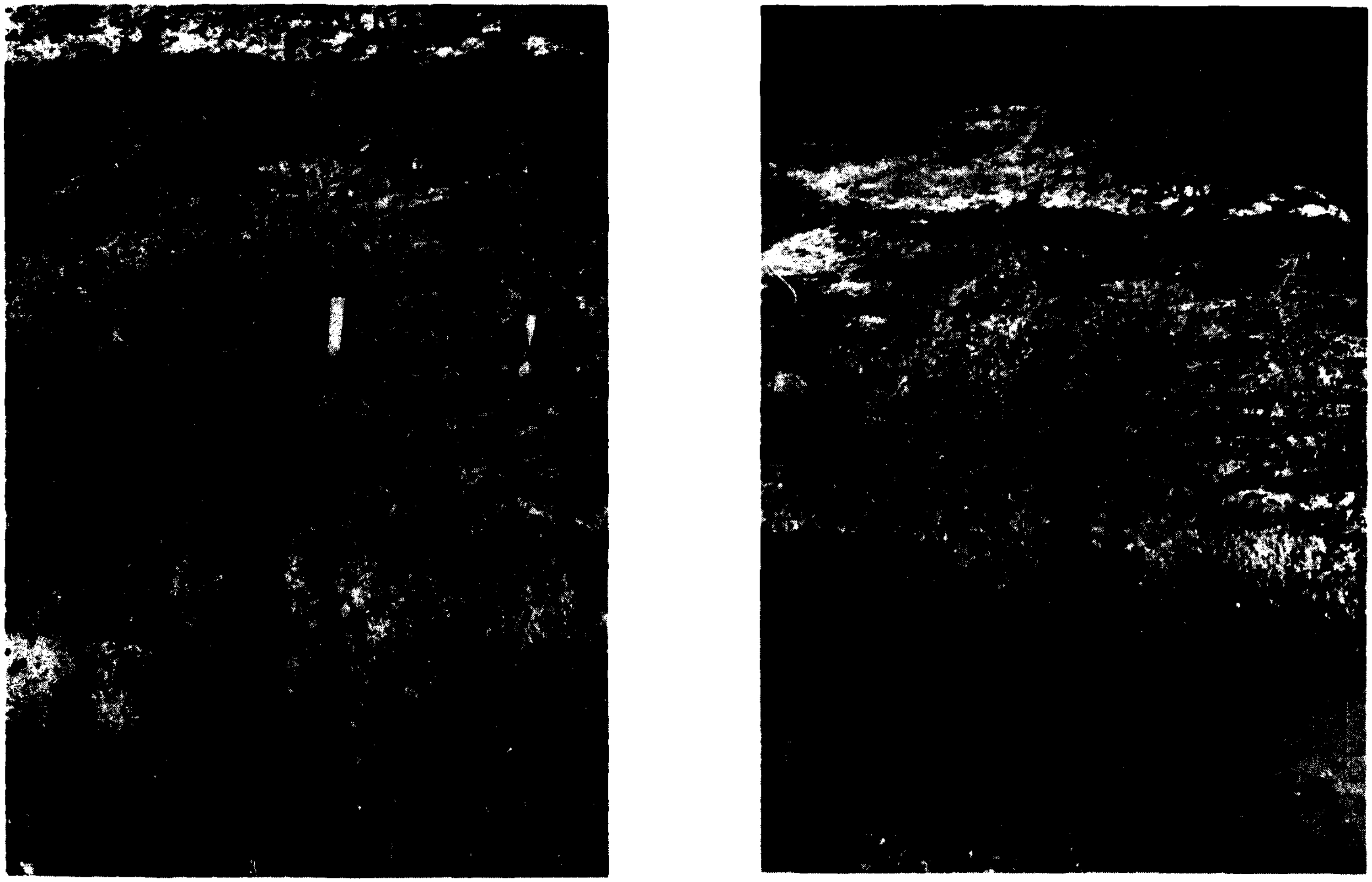
e. Blind gullies below piping zone in bank

f. Piping cavity and blind gully in bank

Figure 10. (Sheet 3 of 3)

which the waters flow. Changes in biological and chemical parameters along the flowpath can cause precipitation of the dissolved species being carried by the seeping water. Deposition of chemical species caused by changes in pressure, Eh and pH as well as microbial activity may form characteristically tinted or colored zones in the soil. Staining, thus, is an indicator of persistent flow of groundwater through a soil zone for a considerable period of time. However, such staining may have occurred in the past, and present conditions in the groundwater flow system may differ markedly from those pertaining in the past. Thus, staining is an indicator of persistent groundwater seepage in the past, but it does not guarantee that such flow will occur again in the future and it does not indicate that the gradient causing the flow will be sufficiently high (or the flow will be sufficiently intense) to cause removal of soil particles from the face of the exfiltration zone. Figure 11 shows several examples of stained zones caused by persistent outflow from bank faces.

29. A third indirect indicator of piping activity is the presence of holes above and behind a streambank. If the soil layers over a pervious soil zone possess sufficient shear strength, a piping cavity will tend to elongate since any shortening of the flowpath from the exfiltration face in the hole to the source of water will tend to increase the gradient. Where the source of water is precipitation or runoff which collects in depressions in the floodplain adjacent to the bank, the piping cavity may eventually reach the water source. This breaching of the soil surface in a floodplain depression is likely to happen if the eroded pipe is located at a shallow depth. In many naturally formed soil profiles, percolating infiltration tends to dissolve and carry minerals and fine soil particles out of the uppermost portion of a soil mass. These particles and/or minerals frequently are deposited a short distance below the zone from which they were removed, to form a layer of low hydraulic conductivity called a fragipan. Infiltrating precipitation subsequently moves down to this layer and then migrates laterally along the top of the fragipan, as interflow. Concentration of this interflow leads to the formation of soil pipes. The overlying soil typically is reinforced with roots of grasses and other forms of vegetation so that very long pipes may form until they extend back to a depression or a weak spot in the overlying soil, at which point the pipe propagates upward to the surface. The holes where soil pipes reach the surface are difficult to find, and they may be



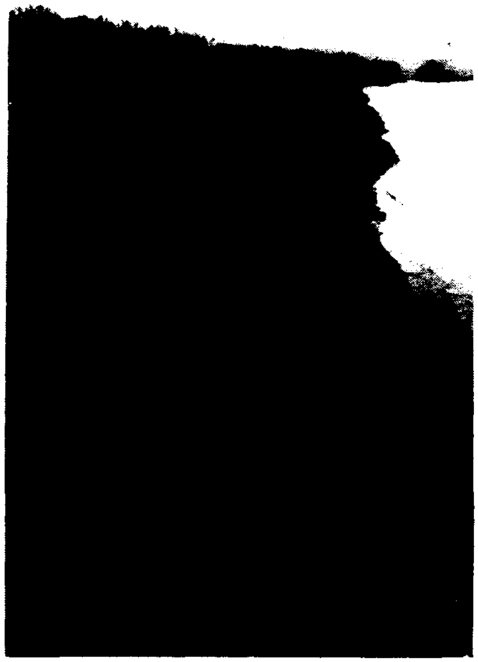
a. Staining at and below piping cavities

b. Staining at and below piping cavities

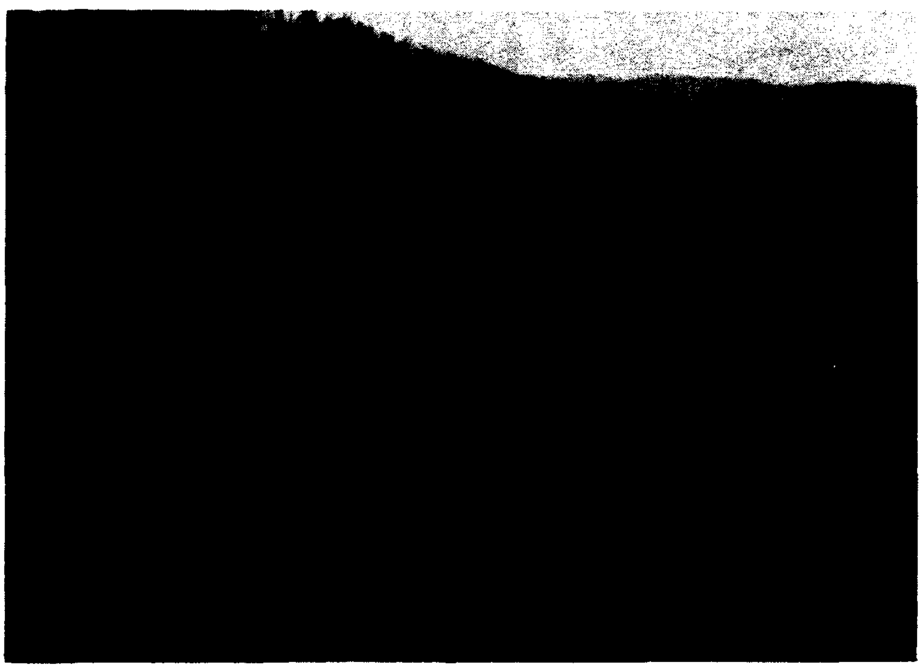
Figure 11. Stained zones caused by outflow from bank faces

located far from the place where the soil pipe reaches an exfiltration face in a rill, gully, or streambank. Thus, holes in the floodplain surface can be indicators that piping is active at a site, particularly at a shallow depth. However, care must be taken to prove that the holes have been caused by subsurface internal erosion and not by some other agency such as a burrowing animal. Figure 12 shows an illustration of piping cavities which extended up to the soil surface behind a streambank.

30. Tertiary indirect evidence. Some features or circumstances on or near a streambank may suggest only the possibility that piping/sapping has occurred since such circumstances may be caused by a number of mechanisms, only one of which is piping and sapping. A number of types of local failures in surficial zones of streambanks can be caused by undercutting of overlying layers when piping/sapping removes underlying pervious zones. Removal of soil particles in a piping zone removes support for overlying layers which then must function as slabs cantilevered out over the piping/sapping cavities. Cantilever action requires the mobilization of tensile stresses in the top fibers of the undermined slabs. Only cemented soils or soils reinforced with plant roots can support tensile stresses indefinitely, so most natural streambank soils soon develop cracks at the upper surfaces of the undermined bank layers. Formation of such cracks reduces the cross section of the cantilevered slab so the cracks inevitably extend downward to the zone of soil removal in the underlying piping/sapping layer. Slabs or chunks of soil are detached by these cracks from the remaining *in situ* soil mass. Figure 13 shows slabs developed by sapping. Quite often, when detached slabs or chunks move downward onto the partially removed piping layer, the slabs or chunks tilt outward (at the tops of the slabs) from the crack face. Support at the front of the slab base is less complete than at the back of the base, since soil removal is greatest nearest the bank face. When root systems provide some degree of tensile reinforcement near the top of undermined cantilevered layers, a shear failure can occur. A slab or chunk is detached from the bank face by formation of a vertical shear plane parallel to the bank face. The aspect ratio of the detached slab or chunk depends on the thickness, unit weight, and strength of the undermined layer. Figure 14 shows detached slabs and chunks on banks where piping/sapping undermined upper-bank layers and caused the observed local failures. Infrequently, removal of support to overlying layers will lead to fall of the lower part of an undercut layer while

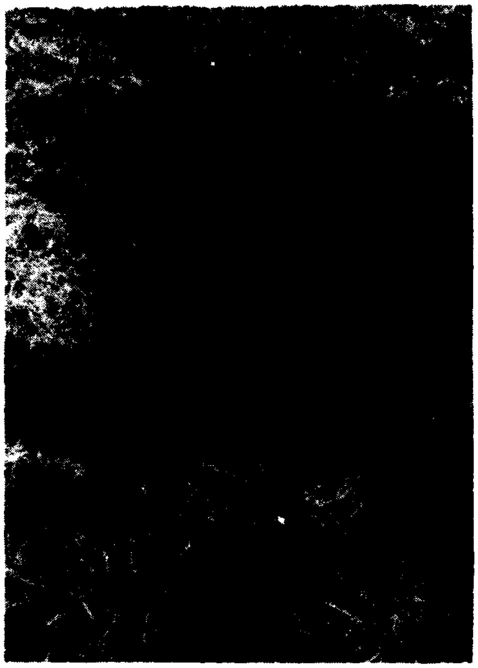


a. Large cusp in bank caused by piping



b. Collapse zone in field adjacent to cusp shown in Figure 12a ("upstream" end of soil "pipe")

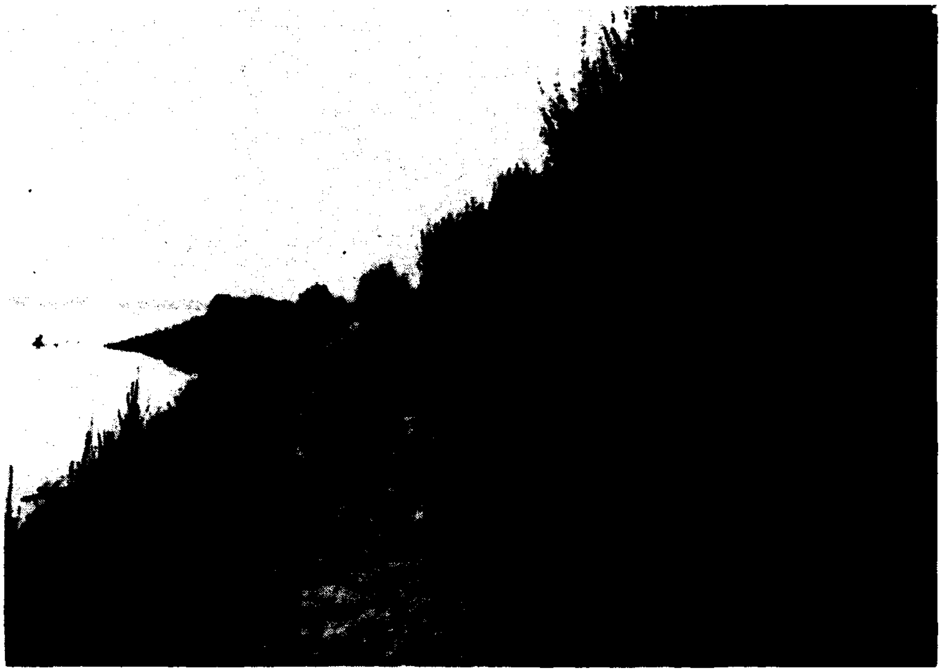
Figure 12. Piping cavities which extend up to soil surface behind a streambank (Continued)



c. Close view of cavity in collapse zone (Figure 12b)

d. Cavity in collapse zone in soil "pipe"

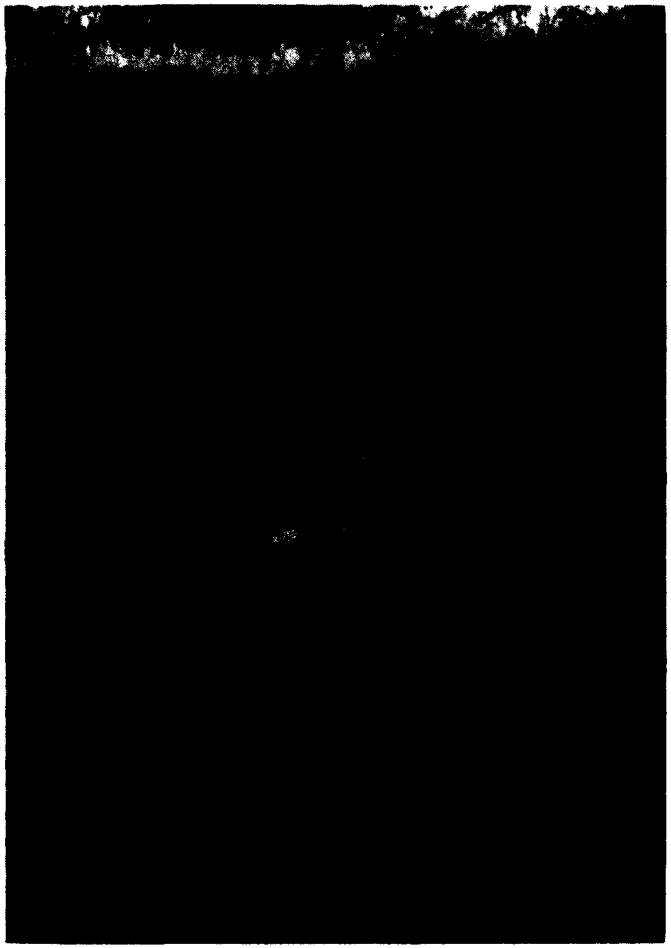
Figure 12. (Concluded)



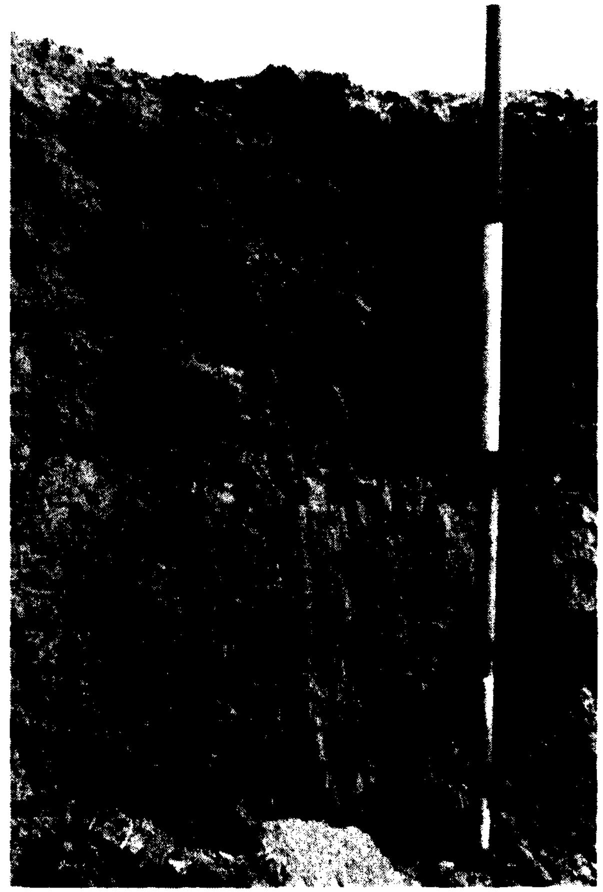
a. Cracks and slabs above sapping zone in bank

b. Slabs in upper bank above sapping zone, Kanawha River

Figure 13. Examples of slabs developed by sapping (Sheet 1 of 4)



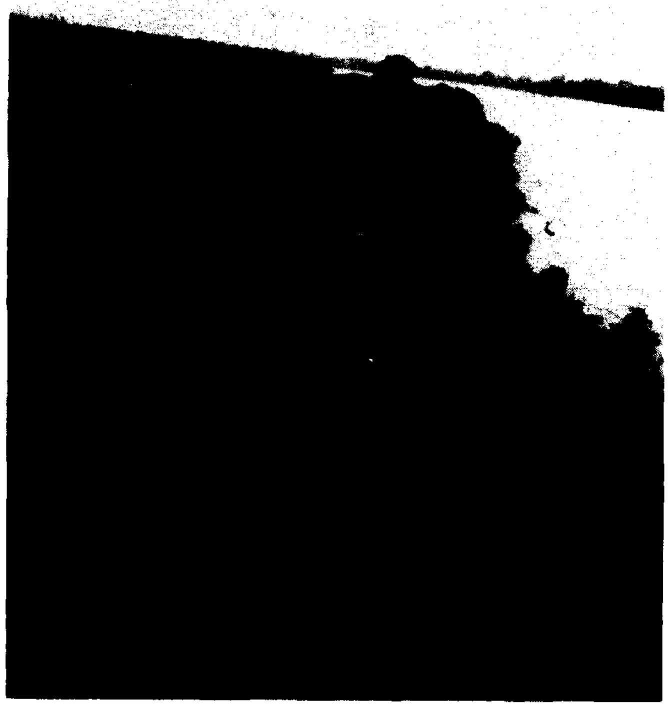
c. Slabs above sapping zone, Red River bank



d. Slabs above sapping zone, Ohio River bank

Figure 13. (Sheet 2 of 4)

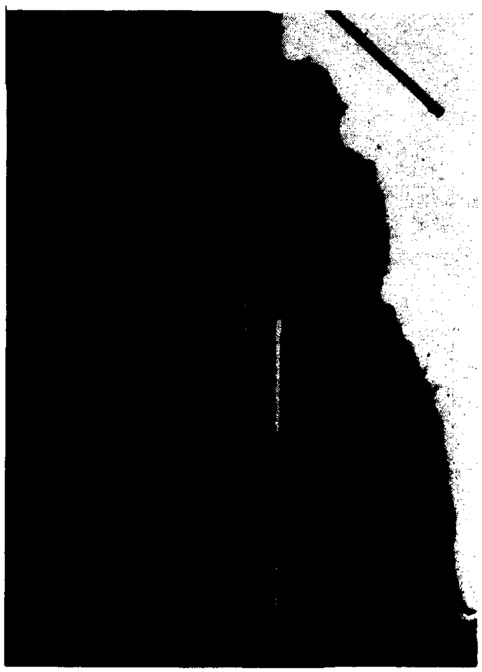
e. Slabs above sapping zone



f. Slabs about to fall, piping in middle bank, undercut slab

Figure 13. (Sheet 3 of 4)

g. Slabs undercut by piping in midheight of bank



h. Close view of slabs in upper bank shown in Figure 13g

Figure 13. (Sheet 4 of 4)

a. Detached slab at site shown in Figure 13g

b. Midbank sapping zone with fallen slabs (foreground) at site shown in Figure 13g

Figure 14. Detached slabs and chunks from undermined upper-bank layers (Continued)

c. Detached slabs (foreground), cracks in upper bank, drain tile in failing slab, site shown in Figure 13g

d. Detached slabs, scarp above sapping zone

Figure 14. (Concluded)

the uppermost parts of the layer remain in place because of the tensile reinforcement furnished by vegetation roots. Figure 15 shows such behavior.

31. When a detached block or slab falls down onto the partially removed underlying piped-out layer, the detached mass may not topple outward from the bank face. If the underlying piped-out layer was relatively thin, the detached mass may move down only a short distance and may appear to be intact, especially when viewed from the stream or from the lower portions of the bank. Such partially displaced slabs and blocks are susceptible to the creation of pressures which tend to push the masses outward from the bank, if water flows down from the surface to fill the cracks behind the slabs or chunks. Water pressures can move fallen slabs or blocks away from their original positions by a combination of force directed toward the stream and uplift. This is possible because water accumulating in cracks behind detached masses also seeps down into the piping zone below the mass and causes uplift pressures against the base of the detached mass. Figure 15 shows blocks and slabs which have been displaced from their original "fallen" positions.

32. The localized failure modes described in the preceding paragraphs are only indirect and uncertain indicators of the operation of the piping/sapping process on a site, because other mechanisms in addition to piping/sapping can cause these types of failures. Undercutting of upper-bank strata can be caused by tractive force scour of lower-bank layers and by wave attack on lower-bank zones. Nearly vertical cracks in a streambank can be caused by a variety of mechanisms including mass slumping failures, expansion as a result of stress relief, and excavation.

33. Another indirect indicator of piping/sapping activity is failure caused by spreading and rapid flow of pervious soil layers. This type of failure is closely akin to the sudden outflow type of failure associated with spontaneous liquefaction of loose, saturated cohesionless strata under the influence of impulse, shock, or earthquake loading. Investigations on a number of sites have shown that piping/sapping at the face of a thick pervious stratum apparently had produced a sudden, very rapid outflow of soil and water from the piping layer toward the stream. Figure 17 shows conditions at one site after an apparent spreading failure initiated by piping and sapping in several of the pervious sandy layers in the bank. The occurrence of this type of failure is only suggestive of the occurrence of piping and sapping prior to

a. Tensile failure caused by piping below upper-bank zone reinforced by roots

b. Small blocks held at top of bank by root reinforcement; failure caused by sapping

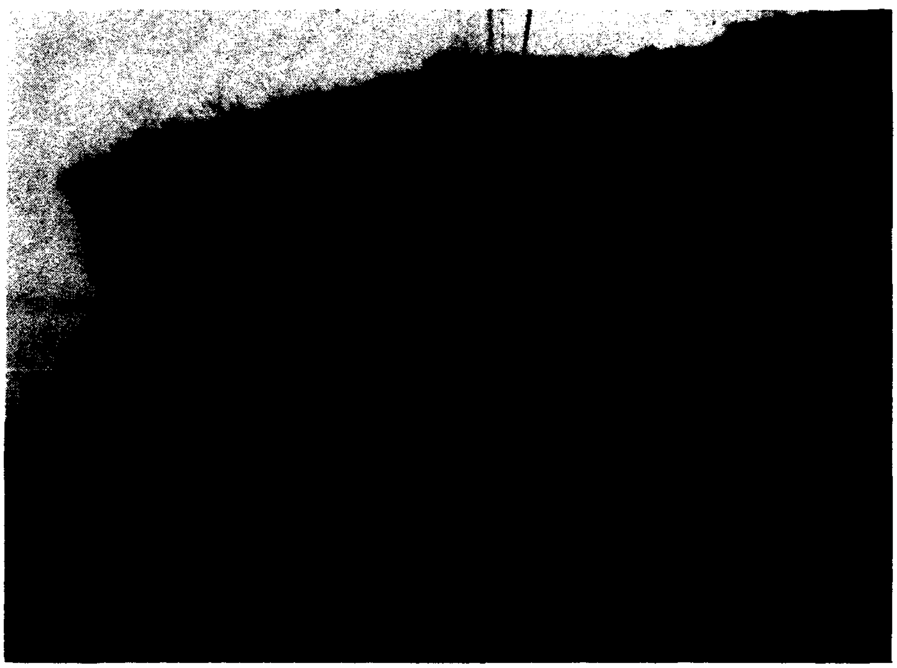
Figure 15. Overlying layers reinforced by vegetation roots remain in place after fall of lower part of undercut layer (Continued)

c. Tensile failures caused by piping below collapsing mid-height layer overlain by cohesive layer

d. Site of failure shown in Figure 15c

Figure 15. (Concluded)

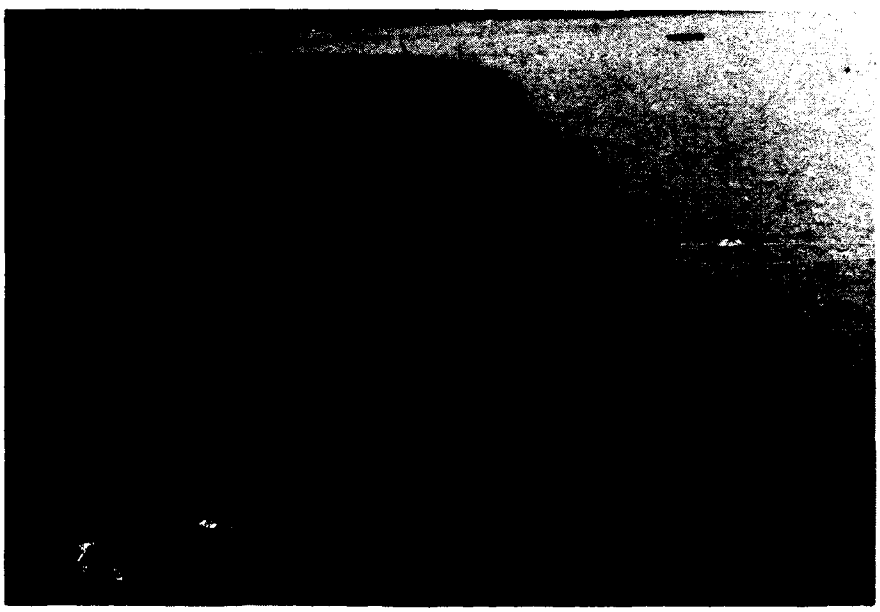
a. Blocks displaced toward stream after sapping undercut upper bank and caused failure



b. Blocks detached and displaced after sapping caused undercut upper bank to fail

Figure 16. Blocks and slabs displaced from original "fallen" position (Sheet 1 of 3)

c. Slab fallen from upper bank above piping zone displaced to edge of stream



d. Slabs and blocks toppled out of low bank undercut by sapping

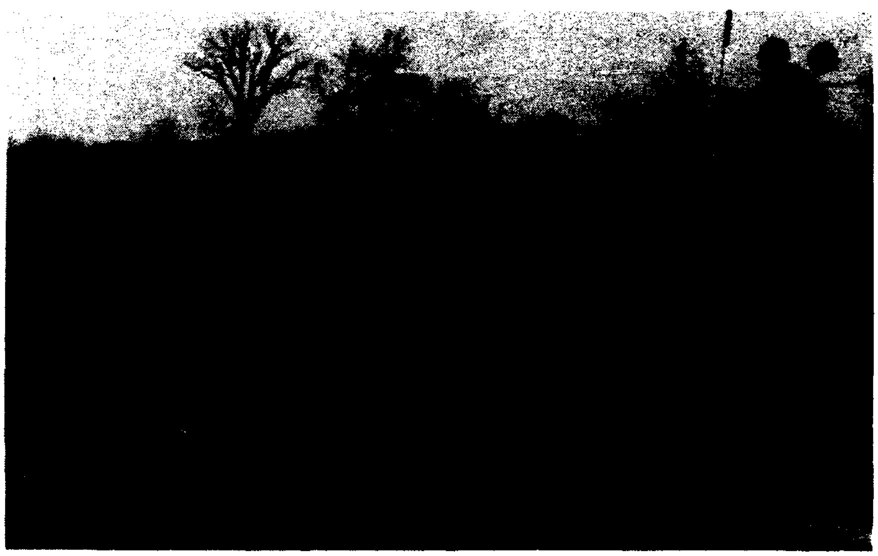
Figure 16. (Sheet 2 of 3)

e. Slab fallen as a result of midheight piping and sapping in bank shown in Figure 13f

f. Slabs fallen as a result of midheight piping and sapping in bank shown in Figure 13f (Note: Moss and algae on toe of bank)

Figure 16. (Sheet 3 of 3)

a. Large cusp at site where piping/sapping caused spreading failure in underlying sand layers



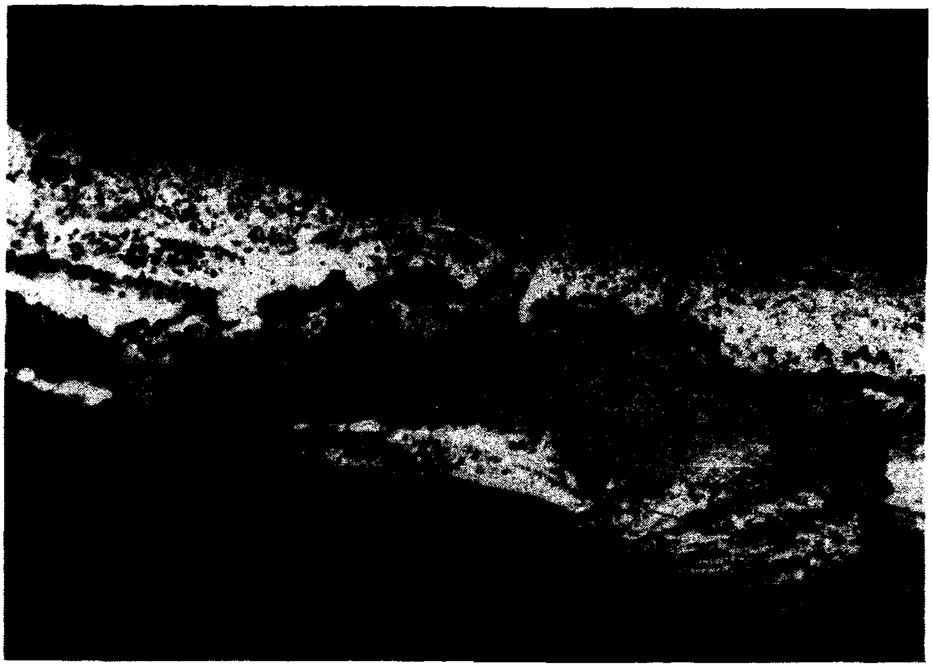
b. Failed slabs at head of cusp shown in Figure 16a

Figure 17. Site of apparent spreading failure initiated by piping and sapping in several pervious sand layers

the failure, since this type of failure can be caused by mechanisms other than piping and sapping.

34. Investigators of bank erosion often conclude that waves have eroded a bank when the bank consists in part of a series of short scarps or nearly vertical faces parallel to the stream, such as the features shown in Figure 18. The features shown in this figure were caused by sapping where water seeped out of thin pervious zones between equally thin less pervious zones. The sandy soils in the pervious sapping zones have been transported out onto the tops of the next lowermost, less pervious layers, and the less pervious layers have formed short, nearly vertical faces as they were undermined by the sapping action. These features can be distinguished from wave-cut benches. Close inspection will show a very irregular alignment of each small scarp; wave-cut benches tend to be very regular in alignment. Viewed from above, each scarp produced by sapping and piping resembles a series of arcs or an irregular line along the length of the bank. Close inspection of the scarps often will reveal reentrant angles at the ends of arcs and other features which could not have been cut by waves striking the bank. These scarps are not conclusive evidence of the operation of piping and sapping activities, because similar features can be created in layers of recently deposited sediments when those layers dewater; the water draining toward the stream from the fresh sediments causes the edges of the sediment layers to be undercut and fail in a mechanism very similar to sapping, but the water does not seep out of the bank proper. Furthermore, these small scarps often are very short-lived, especially if the less pervious layers dry and lose apparent cohesion; the nearly vertical scarps in the drying layers collapse and the final rounded shape of the deteriorated scarp line may be indistinguishable from a similarly dried wave-cut bench line.

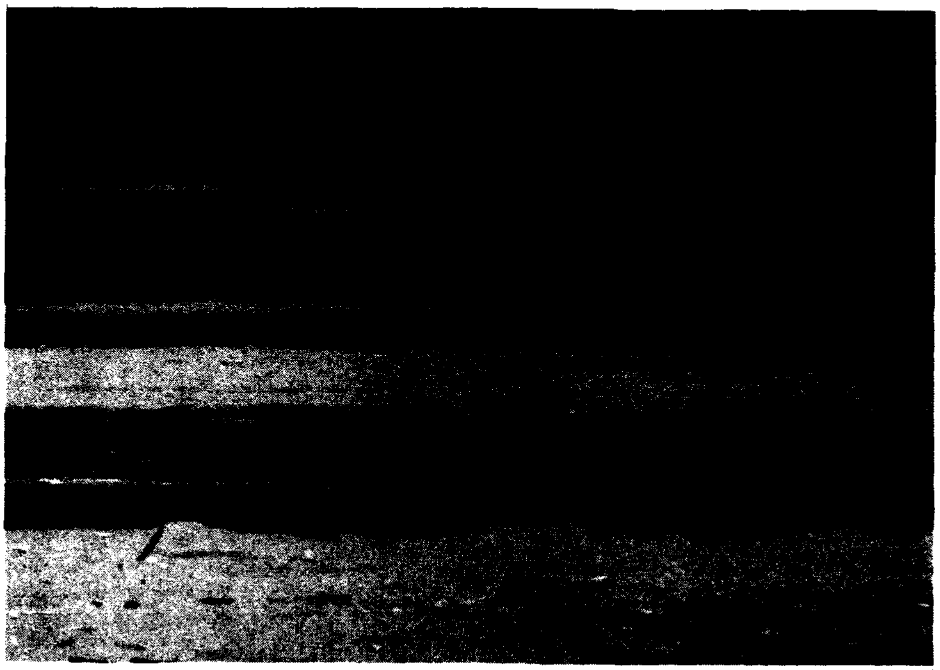
35. On many sites where piping and sapping have occurred and where a minimum depth of water is maintained in the stream for navigation purposes, the bed of the stream immediately in front of the bank showed a very shallow slope. In many cases, this subaqueous shallow slope (or bench or shelf) extended far out toward the stream channel. This feature indicates that current forces have not been sufficiently strong to scour or remove the bank toe but have sufficed to remove the materials displaced by the piping/sapping process. The banks have retreated, above the maintained stream elevation, because of piping and sapping. Thus, this kind of shallow subaqueous bench



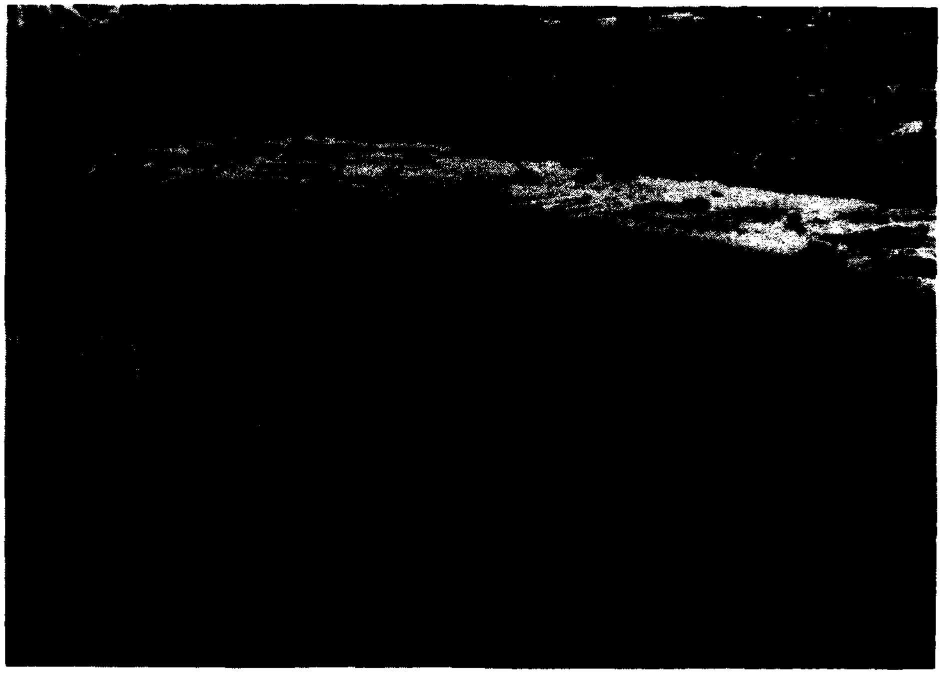
a. Multiple scarps caused by sapping, Illinois River

b. Multiple scarps caused by sapping

Figure 18. Short scarps and vertical faces parallel to stream caused by wave erosion (Sheet 1 of 3)



c. Multiple scarps caused by piping/sapping



d. Close view of scarps caused by piping/sapping

Figure 18. (Sheet 2 of 3)

e. View of multiple scarps caused by piping/sapping

f. Weathered scarps at site shown in Figure 18e

Figure 18. (Sheet 3 of 3)

can be an indirect indicator of the operation of piping/sapping on a site.

36. The last category of indirect evidence of piping or sapping on a site is negative evidence. This type of evidence consists of a lack of features and circumstances which are indicators of other mechanisms of bank failure and erosion, as well as the occurrence of failures at times and in places not appropriate to failure mechanisms other than piping/sapping. For example, mass slumping failures caused by tractive force erosion of the lower portions of a bank and subsequent displacement of the oversteepened slope are characterized by an upper scarp, a rotation of planes in the slumping mass, and a protrusion of the lower parts of the slump mass toward the stream. Trees growing on the slump mass typically are tilted back upslope (upbank) by rotation of the slumping mass. Such conditions are shown in Figure 19. Lack of such evidence at a site where some sorts of failure and erosion are obvious suggests that failure did not occur by mass slumping or sliding. This suggests that piping or sapping may have caused the hitherto unexplained failure.

37. Another sort of negative evidence for piping/sapping is the occurrence of failure and erosion at locations and at times inconsistent with other failure mechanisms. For example, mass sliding promoted by rapid recession of stream waters obviously is not indicated if a failure occurs during a time period when the stream level has not changed significantly. Likewise, both "drawdown" slumping and tractive force undercutting would be contraindicated if failure occurred at an elevation on a bank high above stream level, and lower soil masses were not displaced. Similarly, tractive force scour usually does not occur on the insides or convex sides of bends in a stream; failure and erosion at such locations would suggest that a mechanism other than tractive force scour was operating at those sites. This sort of evidence does not lead to a positive identification of the piping/sapping process but (by process of elimination) can suggest that failure by piping/sapping may be more likely than failure by one or more other mechanisms.

a. First example

b. Second example

Figure 19. Mass bank failure by slumping

PART III: INTERACTIONS WITH OTHER MECHANISMS

38. Identification of the piping/sapping mechanism operating on a site often is made more difficult by the simultaneous operation at that site of other mechanisms of failure and erosion. In one sense, such interaction must occur so that the piping/sapping process is possible or can continue. However, many of the interactions among failure and erosion mechanisms are incidental and not necessary for the continuation of the piping/sapping process.

Necessary Interactions

39. The obvious result of the piping/sapping process is movement of soil particles out of susceptible zones in a bank face, with possible concomitant failure of overlying less pervious layers. The shape of the bank is changed and soil is moved closer to the stream and to lower elevations. If no other process operated, the change in bank conditions would lead eventually to a decrease in hydraulic gradient and cessation of piping/sapping. A berm of displaced soil would be formed on the lower portions of the bank. Change in the geometry of the seepage path and exit conditions would lead to diminishing intensity of internal erosion. The rate of change of bank conditions also would decline steadily, so that the process would approach an equilibrium condition only after a very long time (theoretically, an infinite time would be required). To prolong the occurrence of piping/sapping erosion, the materials moved by this process to the lower parts of the bank must be removed from that area by some other mechanism. In short, if the stream itself does not remove the materials displaced by the piping/sapping process, that process will cease.

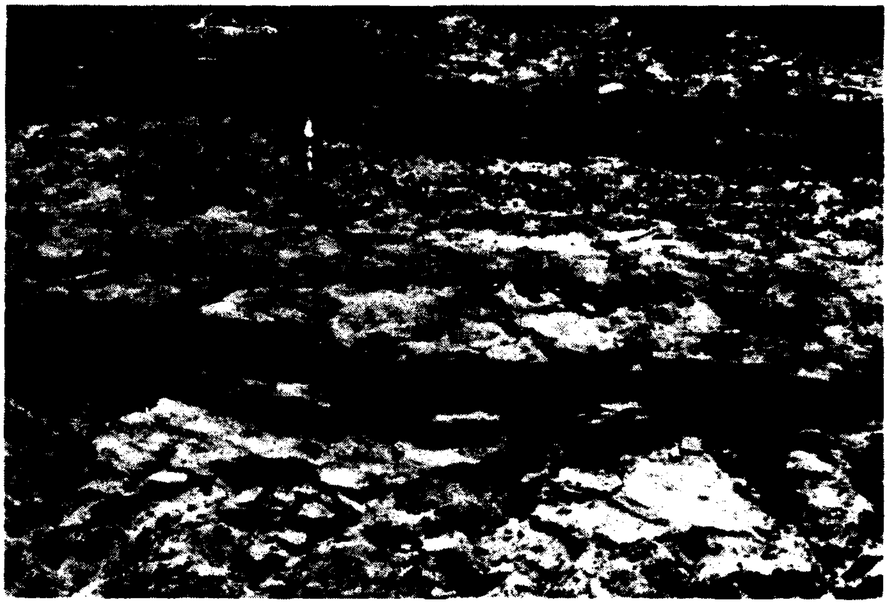
40. A net negative sediment balance must exist at a site for the piping/sapping process to continue. The process may operate intermittently in episodes associated with periods of high water and/or intense precipitation, but such episodes will become less frequent and will eventually cease unless the stream removes more material from the site than is deposited there.

41. The most effective mechanism in removing the products of piping/sapping erosion usually is tractive force scour. Fallen slabs and blocks are obstructions to flow and the consequent turbulence around such obstacles typically is quite effective in eroding such masses. Waves striking

the bank can wet and impact directly on the products of piping erosion. Weathering processes such as wet-dry and freeze-thaw cycles tend to break down the integrity of slabs and blocks. Such ancillary mechanisms may facilitate the removal of piping products by currents during periods of high stage and high discharge. Overland flow and passage of runoff down over a bank may move piping products toward the stream and thus promote their removal. If the net result of all these processes is not removal of material from the site, however, eventually, piping will cease.

Incidental Interactions

42. Given that piping/sapping will cease if the net sediment balance on a site is not negative, the variety of interactions possible between piping and other mechanisms of failure is virtually limitless. During a major flood, for example, soil may be scoured away from the lower part of a bank, but sediments may be deposited on all the nearly level parts of the bank during flood recession. Such sediments may retard piping and sapping action by covering exposed exfiltration cavities and faces. Figure 20 shows a layer of sediments deposited over and in front of piping cavities and piping cavities obscured by the fall of undermined soil. A rotational slump in a bank may sever the hydraulic connection between that part of a layer moving in the failing mass and the rest of the layer in the <u>in situ</u> bank, effectively curtailing flow through the layer and any piping at the exposure of that layer in the bank face. Weathering of surficial layers on the bank face may detach small prismatic blocks of soil which fall and accumulate in front of exfiltration zones, retarding piping/sapping. Vegetation may take root in the loose accumulations of piped-out soil in front of sapping cavities and may act to retain that soil against wind, wave, and current erosion. Growth of vegetation in front of piping cavities may promote deposit of sediments in the vegetation so that exfiltration zones are partially or completely covered and masked. Figure 21 shows a site where piping and sapping had been very active but where accumulation of sediment and growth of vegetation in that sediment completely masked the previously bare bank face. Figure 22 shows the same location as shown in Figure 21, at a prior time when currents had removed the products of piping erosion during a period of high stage and high discharge. The simultaneous operation of different processes on a bank, including deposition of sediments,



a. Sapping zone covered by recent sediments

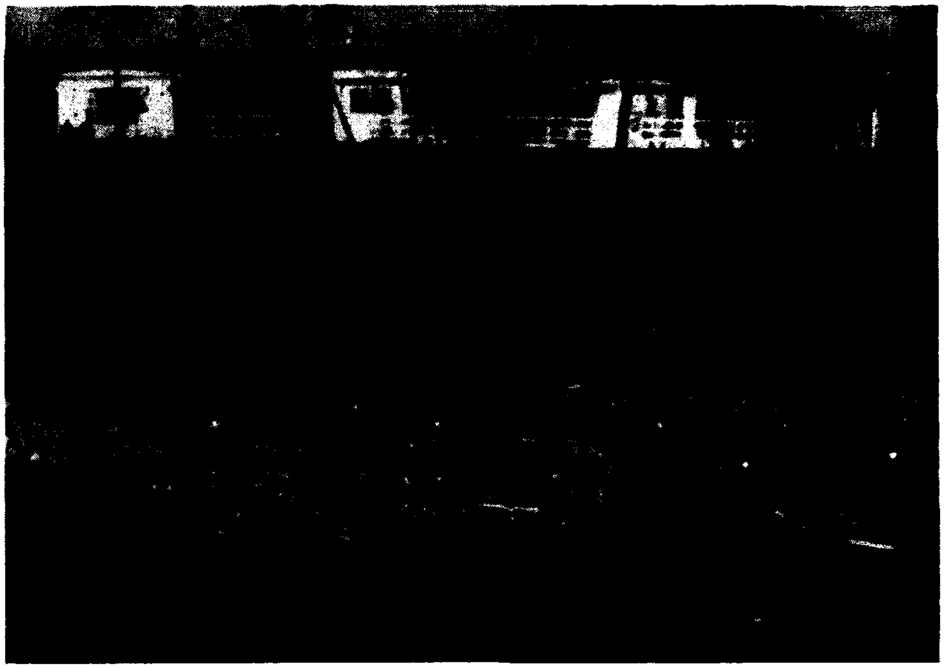
b. Sapping reestablished through sediments deposited over original sapping zone

Figure 20. Piping cavities covered and obscured by different processes (Continued)

c. Example of sapping zone obscured by fall of soil

d. Another example of sapping zone obscured by fall of soil

Figure 20. (Concluded)

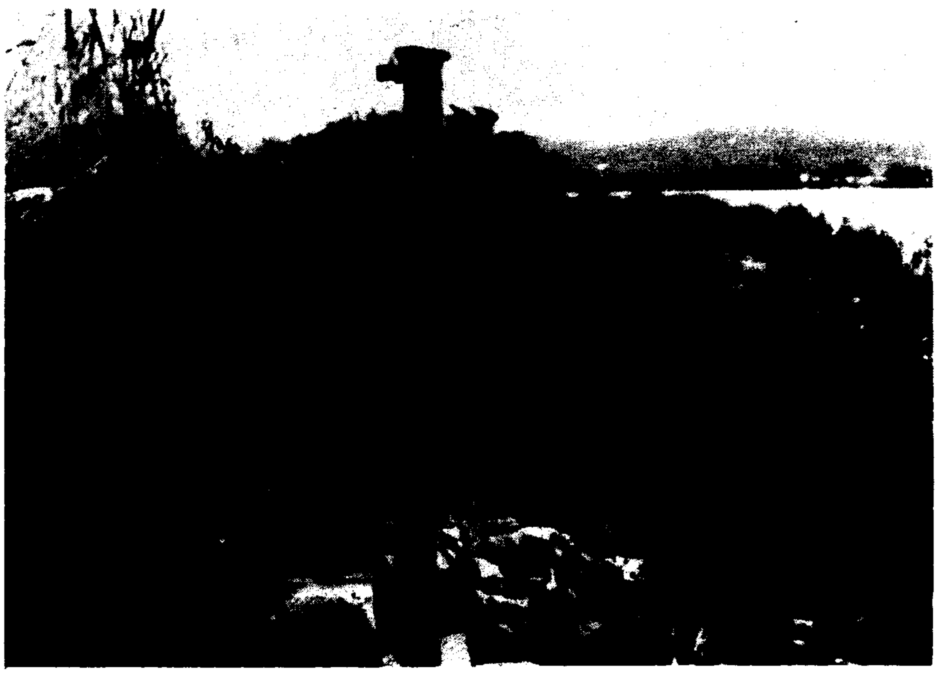


Fiugre 21. Active piping/sapping erosion site; March, 1981

Figure 22. Same site as shown in Figure 21; August, 1986

may mask the evidence of piping activity and make that mechanism very difficult of identify. Similar changes in conditions are shown in Figures 23 and 24. Figure 25 shows bank sites on which piping and sapping had been very active; the feature characteristics of piping/sapping have been obliterated by the operation of other processes.

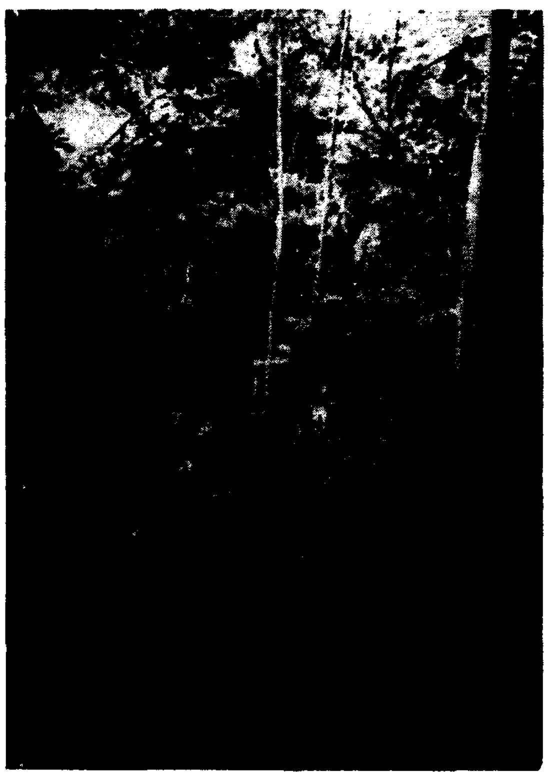
a. Active piping/sapping erosion site; April, 1977



b. Piezometers exposed by piping/sapping erosion at site shown in Figure 24a; March, 1983. (Piezometers had been installed 6 ft (2 meters) behind bank shown in Figure 24a)

Figure 23. Two different stages of erosion at same site within 6 years

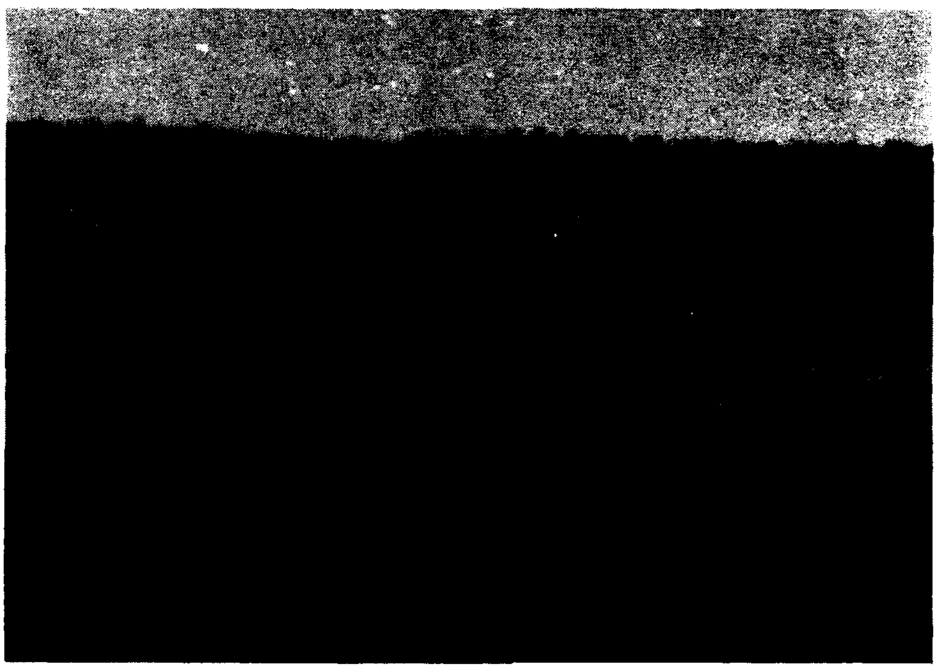
a. Same site shown in Figure 23; August, 1986



b. Piezometers pipe (with flagging) in vegetation on site shown in Figure 23; July, 1988

Figure 24. Later stages of eroded site (same as Figure 23) with heavy vegetation

a. Same site as shown in Figure 23 and 24; March 1977



b. Full view of erosion site

Figure 25. Piping/sapping erosion site

PART IV: PREVENTION AND REMEDIATION

Fundamental Considerations

43. For internal erosion to remove soil from a streambank, a free or exfiltration face must exist and the hydraulic gradient at that face must be sufficient to dislodge particles and carry them away. Prevention or interruption of a piping/sapping process can be achieved if the water causing the internal erosion is removed through a drainage system, or the hydraulic gradient is reduced sufficiently by drainage. Alternately, piping can be stopped if the free exfiltration face is eliminated or altered so that particle removal no longer occurs at that face. If the sediment transport/deposition balance is altered so that the particles removed by piping are no longer removed from the site, a berm of piped-out material eventually will form, the seepage path will elongate, the hydraulic gradient will decrease, and internal erosion will cease. If a more positive approach is taken, the piping/sapping process can be interrupted by placing a filter over the exfiltration face so that the seeping water will pass through the filter but the soil particles in the face will be retained. Obviously, this last alternative requires alteration of site conditions to protect the filter.

44. Site drainage. On sites where piping/sapping is caused by seepage from a localized source of water, the internal erosion may be prevented if positive drainage is provided so that the seeping water is collected and conveyed safely to the stream or to another suitable outlet. For example, piping can occur where agricultural drains are placed with open joints so that collected water leaves the drain system and wets the bank soil around the drain outlet. If the outlet of the drain system in the bank consisted of pipes without joints, the release of water into the bank would be prevented and no piping would occur. On sites where water or wastewater pipes are leaking and causing internal erosion in an adjacent streambank, the leaks can be repaired or positive drains can be installed to remove the leakage safely until the leaks can be found and stopped. Where the source of water feeding a piping/sapping zone cannot be identified readily, positive drainage (e.g. well points) can be provided to remove the water safely from the piping zone. Drains can be installed laterally from the streambank to capture the water feeding the piping process; such drains should be designed to prevent water

entering the drain system from the stream during periods of high water, and should be equipped with filters (e.g. wrapped with a filter geotextile) to prevent loss of soil particles through the drain system. A drainage system need not remove all the water from a piping/sapping zone to stop further internal erosion; if site drainage is altered so that the hydraulic gradient at the exfiltration face is sufficiently reduced, no additional particle removal will occur. On many sites where piping/sapping occurs, however, a principal source of water to supply the piping process is bank recharge from a stream during high-water events. In such circumstances, it may not be feasible to use drainage to prevent piping erosion. If drainage is not feasible or is not attractive economically, internal erosion may be prevented by altering the material balance at the site or by providing a filter system to facilitate exfiltration without removal of bank soil grains.

45. <u>Material balance.</u> On sites where the source of water to a piping/sapping zone is localized in or behind a streambank, or where the flow causing the internal erosion always occurs toward the stream, it may be possible to lengthen the seepage path and reduce the exit hydraulic gradient sufficiently to prevent soil loss at the exfiltration face. For example, if the exfiltration face is high on the streambank and piping occurs most often as a result of precipitation and interflow, it may be possible to place material over the exfiltration face, lengthen the seepage path, and reduce the exit gradient so that piping caused by precipitation infiltration is prevented. Of course, if the stream rises and water is recharged into the bank, placing material over the exfiltration face will not lengthen the seepage path and may not prevent erosion at the surface of the placed material. In the latter circumstance, however, piping/sapping will stop eventually if the soil removed from the exfiltration zone is not transported away from the site.

46. If the overall material balance on a piping/sapping site can be altered to prevent removal of piped-out soils or even to cause deposition of sediments on the bank, the piping/sapping process can be stopped. On some sites, an apparent balance has been observed between the removal and transport of soil from piping/sapping zones and the deposition of sediments over the exfiltration zones where the piping occurred; the piping became reestablished through the sediments as bank recharge seeped out of pervious soil zones, as shown in Figure 21. At other sites, changes in stream flow caused by construction of training structures and dams has caused piping and sapping to

become active in bank faces previously covered with sediments and failed soils, when the altered flow began to remove the sediments and piped-out soils. On many sites, it will not be feasible to alter the material transport regime of the stream, and some form of bank protection may be indicated.

47. Bank protection. Numerous bank protection systems constructed to prevent tractive force erosion or wave attack have failed because piping/sapping activity was not anticipated in the design of the protection system. Exfiltrating seepage can undermine riprap, for example, if the stone is not placed over a filter. Structural systems such as retaining walls and sheet-pile bulkheads also can be affected adversely by underseepage if the hydraulic gradient across the structure is sufficient to initiate piping. Moreover, piping and sapping may be initiated in a bank above a structural protection system if the structure causes the subsurface water level in the bank to rise above the level of the structural protection. Vegetative protection systems designed to promote sedimentation and/or moderate current/wave erosion may counteract piping/sapping activity by altering the materials balance on a site and reducing the rate of removal of piped-out soils. However, vegetative protection systems do not provide any significant direct protection against internal erosion by piping/sapping. Positive protection against piping and sapping requires provision of a filter over the exfiltration face to allow seepage but retain soil particles and a system to retain and protect the filter.

Protection by Filter

48. A filter must allow water to seep out of the bank face while retaining the soil grains in the bank face. The filter, in turn, must be retained and protected against other erosion mechanisms. Continued seepage may cause the filter to deteriorate and maintenance or renovation may be required. A partial degree of protection may be achieved on some sites through the use of locally available labor and materials and innovative techniques.

49. Data required for filter design. Before a filter system can be designed for an eroding bank, the characteristics of the bank soils must be determined. In particular, the variation of relative permeability in the bank is the principal cause of flow concentration, both during exfiltration and during recharge. Slight variations in grain size distribution can cause very

large variations in relative permeability, and an apparently homogeneous soil deposit may show distinct zonation with regard to permeability. If possible, observation of the site should be continued during a period of exfiltration so that all relatively pervious layers can be identified as zones of actual or potential exfiltration and piping.

50. If it is not possible to identify potential piping zones by observation of on-going piping or by inference from evidence of past piping activity, the potential piping zones can be identified on the basis of grain size distribution. Granular layers with little or no fines will be flow concentration zones if other bank soil layers are more fine-grained and less pervious. In a sequence of silt layers and clay layers, the silt strata will be more permeable, flow will be concentrated in those layers rather than in the clay layers, and the silts would tend to be removed and eroded if the hydraulic gradients during exfiltration were sufficient to initiate particle removal. Determination of grain size distribution and inferred relative permeability will indicate zones of potential internal erosion which will require protection by filter placement. Grain size distribution data also are required for determination of grain size limits for filter layers.

51. Filter criteria/design. Grain size limits for mineral filters have been established in terms of the grain sizes of the soil layers which require protection. Criteria for mineral filters are given in Table 1. Alternatively, filter protection can be provided by means of a geotextile system. Criteria for geotextile filters are given in Table 2.

52. Detailed design of filters is not covered here. However, general design considerations can be described. Placement of mineral filter layers or sheets of geotextile filters requires a relatively smooth and regular surface. Irregularities in a bedding surface can be treated by provision of additional thickness in a mineral filter, but filter material of select grades usually is much more expensive than unprocessed sand or mixed-grain texture soils. A bedding layer should be at least as permeable as the most pervious bank layer to be protected. Filter criteria should be applied with due consideration for the grain size distribution of any bedding material. The bedding surface for a geotextile filter should be smooth and regular to avoid concentration of load and damage to the geotextile when the geotextile is installed and when material is placed over the geotextile to retain and protect it. Transition zones should be provided at the top, the bottom, and the edges of the filter

Table 1

Mineral Filter Criteria

Filter Criteria	Soil Protected
$D_{15} / D_{85} < 5$	Sands, silty sands
$D_{15} < 0.5$ mm	Clayey silts
$D_{15} < 0.3$ mm	Silts, low plasticity

D_{15} - particle size in filter for which 15 percent by weight of particles are smaller.

D_{85} - particle size in soil to be protected for which 85 percent by weight of particles are smaller (similar for D_{15}).

(After Sherard, J. L., Dunnigan, L. P., and Talbot, J. R., 1984 (Jun) a and b).

Note: $D_{15} / D_{15} > 5$ to promote drainage.

Table 2

Geotextile Filter Criteria, Geotextile Opening Criteria

Relative Density of Soil to be Protected	$1 < CU < 3$	$CU > 3$
Loose	$O_{95} < CU(D_{50})$	$O_{95} < \frac{9}{CU} (D_{50})$
Medium	$O_{95} < 1.5\ CU(D_{50})$	$O_{95} < \frac{13.5}{CU} (D_{50})$
Dense	$O_{95} < 2\ CU(D_{50})$	$O_{95} < \frac{18}{CU} (D_{50})$

O_{95} = apparent opening size of geotextile or equivalent sieve size opening (Corps of Engineers CW-02215 (Headquarters, Department of the Army, 1987); American Society for Testing and Materials (ASTM) Method D4751 (ASTM 1987)).

CU = uniformity coefficient for protected soil, D_{60} / D_{10}.

D_{50} = particle size in soil to be protected for which 50 percent by weight of particles are smaller (similar for D_{60}, D_{10}).

(After: Giroud, J. P. 1982).

Geotextile Permeability Criterion

k (geotextile) > 0.1 k (soil)

k = hydraulic conductivity

so that internal erosion is not initiated at the boundaries of the treatment. The bedding layer and protective layers, as well as the filter itself, should be designed with due consideration for slope stability; i.e., bank treatment slopes should be selected with attention to overall bank stability as well as sliding stability of each layer in the treatment.

53. Protection of filter. Internal erosion can occur at sites where other erosion mechanisms are active. Filter systems must be protected against the effects of those other processes, as well as against vandalism. The most frequently used protection for bank filters has been riprap. Design procedures for riprap systems are well established and will not be given here. Of primary importance to the design of such systems, however, is identification of all erosive processes which are likely to operate on the site and estimation of the magnitudes of waves, currents, and overbank flow quantities. Most efficient design of the riprap system may require direct observation of waves and currents on the site, rather than reliance on computerized simulations or empirical rules.

54. On some sites, it may be possible to incorporate use of vegetation into the system used to protect the filter. However, care must be taken to avoid detrimental effects of intrusion of vegetation into the filter system. Also, if a vegetative protection system causes deposition on a site, exfiltration through the filter may remove the deposited sediments; the filter will not protect overlying materials.

55. Deterioration of filters. Filters must be protected against the effects of erosion mechanisms other than piping, but even a well-protected filter may deteriorate with time and become less effective. Geotextile filters may be affected negatively by exposure to ultraviolet radiation or by direct contact with chemically active seeping water. Mineral filters are not affected by radiation and may be more resistant to corrosion than are geotextile filters, but both geotextiles and mineral filters may be affected by clogging. Chemically neutral water seeping through a bank may cause clogging of a filter if the soil in the exfiltration zone is gap-graded; that is, if the soil zone consists of grains widely different in size with no intermediate size particles. The much smaller particles which fill the voids between the much larger grains may be transported by the seeping water out to the bank face to form a clogging layer at the interface between the filter and the underlying bedding layer. Additionally, chemically active waters may deposit

material in the filter as a result of changes in pressure, temperature, and other parameters as the water emerges from the bank. Research on clogging is being done at several institutions at the present time. Formation of a clogging layer may reduce the permeability of the filter to the point where pore-water pressures increase against the clogged filter and displace it from the bedding layer. Drains fitted with filters could be used to alleviate such a problem, but continued maintenance of the system could be required under such circumstances.

Innovative Techniques

56. Construction of a filter and filter-protection system over the full height of the bank at a piping/sapping site may be both expensive and unnecessary. An economical alternative may include placement of a filter with overlying protective system only at bank zones showing significant piping/sapping erosion effects, and reshaping of intervening bank zones to resist other mechanisms of instability and to support the filter/protection systems. If the piping/sapping activity is restricted to only a few relatively thin zones, it may be possible to obtain a significant degree of protection by placing a self-contained filter against the faces of the piping zones. For example, if sand satisfying filter criteria for grain size is available locally near the site, it may be possible to fabricate bags or tubes of geotextile into which the sand could be packed; the filled bags or tubes could function to prevent soil loss at exfiltration faces, and the weight of the filled containers could be sufficient to resist displacement by other erosion mechanisms.

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